LEVEL II

AD A090720

TECHNICAL REPORT GL-80-6

PARTIAL FIELD VALIDATION OF THE SURFZONE TRANSITION ANALYTICAL METHODOLOGY (STAM)

by

Gerald W. Turnage

Geotechnical Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

September 1980

Final Report

Prepared for Civil Engineering Laboratory
U. S. Naval Construction Battalion Center
Port Hueneme, Calif. 93043

(14) WES/MP/GL-80-6

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report GL-80-6	2. GOVT ACCESSION NO. AD-A090720	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) PARTIAL FIELD VALIDATION OF THE SURFZONE TRANSITION ANALYTICAL METHODOLOGY (STAM)		5. TYPE OF REPORT & PERIOD COVERED (9) Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Gerald W. Turnage		8. CONTRACT OR GRANT NUMBER(s) (12) 80
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Geotechnical Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Civil Engineering Laboratory U. S. Naval Construction Battalion Center Port Hueneme, Calif. 93043		12. REPORT DATE (11) September 1980
		13. NUMBER OF PAGES 75
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Coastal zone
Mathematical models
Mobility
Ocean bottom vehicles
Surfzone Transition Analytical Methodology (STAM)
Trafficability
Vehicle Performance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results from field tests of the full-size tracked Surfzone Test Vehicle (STV) conducted over a two-week period at two sandy beach/nearshore sites were used to investigate some key vehicle performance prediction relations in the trafficability submodel of the computerized Surfzone Transition Analytical Methodology (STAM). Analysis of the STV test results, along with results from related tests of full-size tracked vehicles and model tracks, demonstrated that STAM equations for predicting the drawbar pull and total motion resistance of

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

411412

JCB

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. Abstract (Continued)

tracked vehicles are adequate and, in fact, slightly conservative for nearly all coarse-grained soil/tracked vehicle/vehicle submergence conditions. For extreme conditions of low coarse-grained soil strength and high tracked vehicle ground contact pressure, modifications were made to the trafficability submodel relations to predict significantly smaller values of tracked vehicle drawbar pull. Finally, suggestions were presented for needed model and prototype testing to validate prediction relations in STAM's other two submodels--the water force calculations and vehicle stability submodels--as well as prediction relations in yet unvalidated parts of STAM's trafficability submodel (primarily relations for obstacle override and for tracked vehicle operation in fine-grained soil near-shore areas).

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

PREFACE

The study reported herein was conducted in a joint effort involving personnel of the Civil Engineering Laboratory (CEL), U. S. Naval Construction Battalion Center, Port Hueneme, Calif.; the Pacific Missile Test Center (PMTC), Point Mugu, Calif.; and the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. WES participation in the study was requested and sponsored by CEL.

The plan of tests was developed jointly by Dr. P. J. Valent of the Foundation Engineering Division (FED), Ocean Engineering Department (OED), CEL, and Mr. G. W. Turnage of the Methodology and Modeling Research Group (MMRG), Mobility Systems Division (MSD), Geotechnical Laboratory (GL), WES. Field tests of the full-size tracked Surfzone Test Vehicle (STV) were conducted during 3-14 September 1979 at two PMTC beach/nearshore sites. The STV field test crew included CEL and PMTC personnel directed by Dr. Valent; Mr. Turnage, who served as technical advisor to Dr. Valent; and Mr. B. E. Reed of the Dynamics Branch (DB), Instrumentation Services Division (ISD), WES, who assisted CEL test personnel in the installation and checkout of test vehicle instrumentation. The field test data were reduced and analyzed at the WES under the direction of Mr. Turnage. Mr. D. E. Barnes of the Operations Branch (OB), Geomechanics Division (GD), Structures Laboratory (SL), WES, computer-coded the modifications to the Surfzone Transition Analytical Methodology (STAM) that arose from analysis of the STV field tests. Mr. Turnage was the author of this report.

The work at the WES was performed under the general supervision of Mr. J. P. Sale and Dr. D. C. Banks, Former Chief and Acting Chief, respectively, GL, and Mr. B. Mather, Acting Chief, SL; Messrs. E. S. Rush and A. A. Rula, Former and Present Chief, respectively, MSD, Mr. F. P. Hanes, Chief, ISD, and Dr. J. G. Jackson, Jr., Chief, GD; and Messrs. G. C. Downing and R. C. Sloan, Chiefs, DB and OB, respectively. The study was under the direct supervision of Mr. C. J. Nuttall, Jr., Chief, MMRG, WES.

COL John L. Cannon, CE, and COL Nelson P. Conover, CE, were Commanders and Directors of the WES during this study. Mr. Fred R. Brown was the Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric as follows:

Multiply	By	To Obtain
degrees (angular)	0.01745329	radians
feet	0.3048	metres
feet per minute	0.3048	metres per minute
gallons per minute	3.785412	cubic decimetres per minute
horsepower (550 ft-lbf/sec)	745.6999	watts
horsepower (550 ft-lbf/sec) per ton	83.82	watts per kilonewton
inches	2.54	centimetres
kips (force)	4448.222	newtons
miles (U. S. statute) per hour	1.609344	kilometres per hour
pounds (force)	4.448222	newtons
pounds (force) per cubic inch	0.2714	meganewtons per cubic metre
pounds (force) per square inch	6894.757	pascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square inches	6.4516	square centimetres
tons (force)	8896.444	newtons

PARTIAL FIELD VALIDATION OF THE SURFZONE TRANSITION ANALYTICAL METHODOLOGY (STAM)

PART I: INTRODUCTION

Background

1. The U. S. Navy has a need for bottom-crawling vehicles to support its work in the survey, construction, and maintenance of near-shore underwater facilities. To use such vehicles effectively, the Navy recognized that a methodology needed to be developed for the rational design or selection of a given bottom-crawling vehicle to satisfy stated performance requirements in a specified seafloor environment. Toward that end, the Navy's Civil Engineering Laboratory (CEL) sponsored work by the U. S. Army Engineer Waterways Experiment Station (WES) to develop a computerized mathematical model that predicts the trafficability performance and stability of nearshore bottom-crawling vehicles. The resulting study* describes (a) the development of this model, the Surfzone Transition Analytical Methodology (or STAM); (b) STAM applications to several CEL-supplied example (hypothetical) vehicle performance problems; and (c) a parametric analysis of STAM-described vehicle design/vehicle performance interactions.

Purpose

2. As a follow-on to the study described,* the present study addresses some important aspects of the field validation of STAM. In particular, the purposes of the study reported herein were:

---

* G. W. Turnage and W. C. Seabergh. 1978. "Study and Parametric Analysis of Trafficability, Running Gear, and Stability Considerations for Nearshore Bottom-Crawling Vehicles," Technical Report M-78-3, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

a. To evaluate the trafficability performance obtained in field tests of a specially built, full-size tracked test vehicle relative to the performance predicted by STAM for the vehicle and environmental conditions tested.

b. To modify STAM, based on the above evaluation and on the analysis of related tracked vehicle and model track test results, for the purpose of accurately predicting the trafficabiity performance of bottom-crawling tracked vehicles in coarse-grained soil nearshore regions.

c. To recommend areas of further research needed to provide a comprehensive validation of STAM.

Scope

3. The scope of the present study is limited in that only one vehicle was tested at three levels of test load in straight-line drawbar pull (trafficability) tests at two sandy beach/nearshore sites of fairly gentle slope. The STAM was developed to describe the influence of a broad range of vehicle physical characteristics on several types of tracked vehicle performance within a variety of nearshore environments. Because the tracked vehicle field test data can be used to validate only a small part of STAM, this report also makes recommendations for further validation testing and analysis.

PART II: TEST PROGRAM

Test Vehicle

4. The full-size tracked Surfzone Test Vehicle (STV)* was designed and fabricated by a private engineering firm under contract to CEL. The STV was built specifically to be operated as a test vehicle in the nearshore region—i.e., the STV was designed to be powered and controlled hydraulically by an onshore source and to have its performance monitored by onshore recording equipment as the STV moved about either on the beach or on the nearshore seafloor. For the tests reported herein, the STV was used to carry deadweight payloads and to develop drawbar pull.

5. Figure 1 shows the STV, and the following listing presents values of some of this vehicle's major physical and operational characteristics.

STV Characteristic	Value
Vehicle weight (unloaded, in air)	12, 50 lb**
Vehicle length	152 in.
Vehicle height (without payload)	46 in.
Vehicle width	93 in.
Ground clearance	16 in.
Track length in contact with ground	123 in.
Track width	24 in.
Vehicle test speed, minimum	1 ft/min
maximum	60 ft/min
Developable force per track (pull on a hard surface)	13,000 lb

6. Table 1 lists the values of STV physical characteristics needed to exercise all three submodels of STAM (the water force calculations, trafficability, and stability submodels) for the three payloads used in the test program reported herein (0 lb, 5,400 lb, and 10,400 lb).

---

* For convenience, symbols used in this report are listed and defined in the Notation (Appendix B).

** A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

Figure 1. Surfzone Test Vehicle

Further comments herein relating to Table 1 will be made only in reference to the STAM trafficability submodel.

7. Because the STV can operate at water depths from zero to full STV immersion, it was appropriate to determine the changes in values of those STV physical characteristics that are significantly dependent on depth of immersion. For example, in parts a, b, and c of Figure 2, the three sets of data points illustrate values of STV buoyant weight (also termed vehicle effective weight) measured in water tank tests at various depths of STV immersion for payloads of 0, 5,400 and 10,400 lb, respectively. The STV's geometry is complex and its specific weight is nonuniform, so that the pattern of STV weight versus immersion depth described by each set of data points in Figure 2 is irregular. For each of the three payloads, however, a separate straight-line relation was determined that could predict STV buoyant weight within 200 lb for the full range of STV immersion. Equations of these relations are shown in

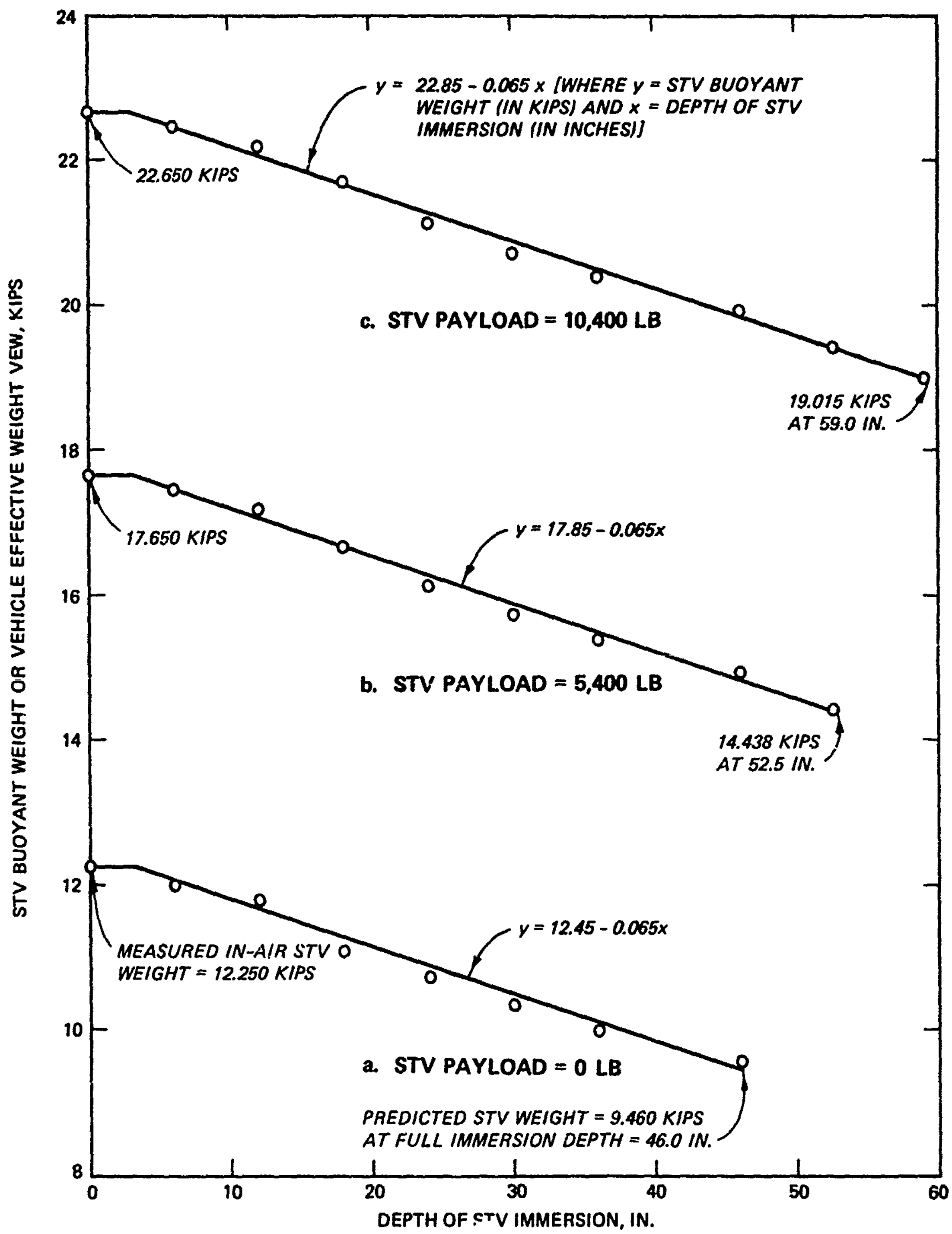


Figure 2. Relations of STV buoyant weight to depth of STV immersion for payloads of 0, 5,400, and 10,400 lb

Figure 2, with STV full immersion depths identified at the right end of he three relations. The maximum percentage error that results from applying each of these relations is 1.6 (predicted value of 12,450 lb versus measured value of 12,250 lb at zero immersion and zero payload). Even this small error was reduced somewhat by using measured in-air STV weight instead of predicted STV weight for immersion depths small enough to cause the predicted weight to exceed the STV's in-air weight. (See the left end of the three relations in Figure 2.)

8. In the trafficability submodel part of Table 1, the STV physical characteristics that are changed by depth of immersion include gross vehicle weight GVW , FLEW (defined in Appendix B and, without a measured value available, taken to equal two times GVW), and those geometric characteristics influenced by the location of the STV's center of gravity, or CG . These characteristics include CGF , CGH , DCG , ACG and DRISCG , each of which is defined in Appendix B and described by the sketch on the last of page of Table 1.

9. The CG's of the 5,400- and 10,400-lb payloads were aligned directly above the CG of the STV without payload, so that the value of CGF was constant for all STV payload and immersion conditions tested. In-air values of CGH were significantly different for the three test payloads (CGH values of 1.1, 10.5, and 16.7 in. for payloads of 0, 5,400, and 10,400 lb, respectively). For a given constant payload, however, measured values of CGH varied within a range of only about 2 in. for the full range of STV immersion conditions (from in-air to fully immersed). Accordingly, it was judged sufficient to use the measured in-air values of CGF and CGH . Since DCG , ACG and DRISCG are each defined relative to the values of CGF and CGH , the values used for DCG , ACG and DRISCG also were those measured or computed for the STV in-air condition.

10. The only other STV physical characteristics in Table 1 that deserve special discussion are the coordinates of the drive sprocket speed DSS versus tractive force TF curve. Interest in these coordinates arises because of the unusual power supply and operational characteristics of the STV. The STV was constructed to be powered and

controlled remotely via hydraulic lines from an onshore power source. This source was a 120-hp diesel engine that drives two onshore pumps which act in parallel and could be operated independently to input up to approximately 41 hp per pump at maximum STV vehicle speed, 60 ft/min. Power from the pumps to the drive sprockets was delivered via 3/4-in. hydraulic lines from the onshore pumps to the STV's on-board hydraulic drive motors and from there through reduction gearing to the drive sprockets. Correlation was established experimentally between STV track speed and the hydraulic flow rate in the return line from the STV motor (one correlation per track). The flow to each track was controlled at the onshore power source, thus allowing remote steering and speed control of the STV.

11. The power supply, gearing, and track systems of the STV were designed to develop large values of STV tractive force that descrease only slightly with increasing values of drive sprocket speed, as evidenced by the calculated values of the DSS versus TF coordinates in Table 1. (Values of DSS in Table 1 are expressed both in feet per minute and in miles per hour, the latter in keeping with the convention established for the STAM trafficability submodel.* Values of TF in Table 1 are for the STV as a whole, not for each track.) Lower and upper limits of STV forward speed are from slightly under 1 ft/min to slightly over 60 ft/min. Because (a) the STV tends to lug (i.e., to jerk or become unstable in maintaining constant speed) at speeds much below 10 ft/min and (b) seafloor work operations involving bottom crawlers are expected to be conducted at speeds not much greater than 30 ft/min, the range of vehicle speeds used in the STV tests described herein was 10 to 30 ft/min. For this range of speeds, maximum values of hydraulic horsepower input from each onshore pump ranged from about 10 to 35.

---

* Turnage and Seabergh, op. cit., p 5.

Test Sites

12. The two sites used for testing the STV are located at the Pacific Missile Test Center (PMTC), Point Mugu, Calif. As shown near the bottom in Figure 3, site 1 is southeast of and adjacent to a large pier near the end of Arnold Road in the southwest corner of the PMTC. Site 2 (near the top in Figure 3) is east of Laguna Point, near Jet Engine Test Building 731. Photographs a and b in Figure 4 show the STV being tested at sites 1 and 2, respectively.

13. Each of the test sites was in a sandy beach/nearshore area, but characteristics of the sands at the two sites were markedly different in some respects. While both the site 1 and the site 2 sands are classified SP according to the Unified Soil Classification System, the curves in Figure 5 show that the site 1 sand is considerably more uniformly graded and includes much less large grain-size material than the site 2 sand. Soil property data at the bottom of Figure 5 show that the site 1 and site 2 sands also differ significantly in terms of ranges of values of laboratory dry unit weight and of void ratio.

14. Each test site was required to have (a) acceptable values of ground slope both on the beach and from the beach out approximately 250 ft into the Pacific Ocean, and (b) a range of nearshore soil strengths suitable for testing the STV. These criteria were satisfied in that site selection measurements taken a few weeks before testing showed that (a) average slope values over at least 50 ft of horizontal distance averaged about 2 percent at site 1 and ranged up to about 8 percent at site 2 (i.e., slope values were generally small, but covered a useful range of values, particularly at site 2), and (b) values of average cone index in the 0- to 6-in. soil layer ranged from about 30 to 70 over most of the test area at each of the two test sites (i.e., soil strength was moderately weak, but covered a fairly wide range of values at sites 1

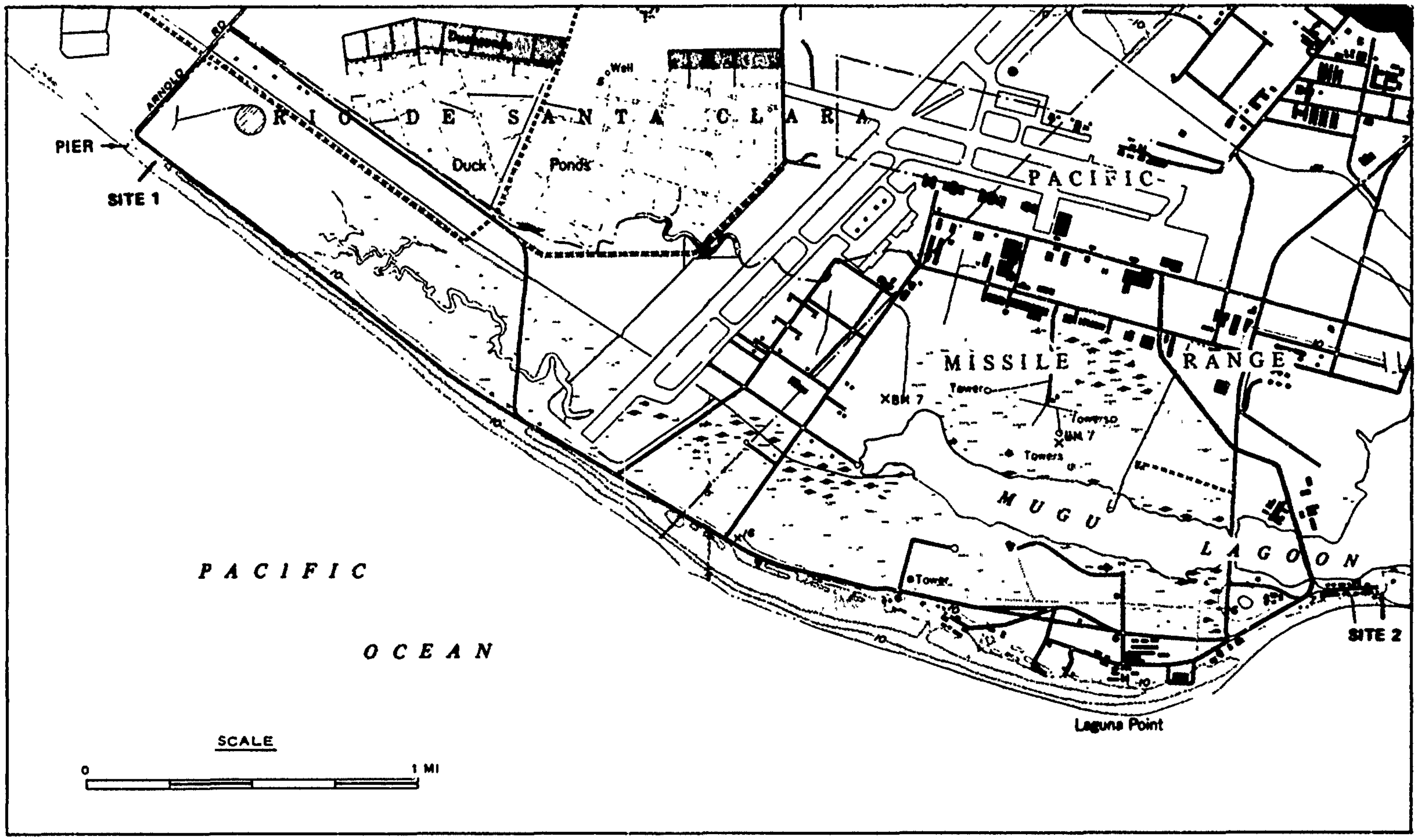
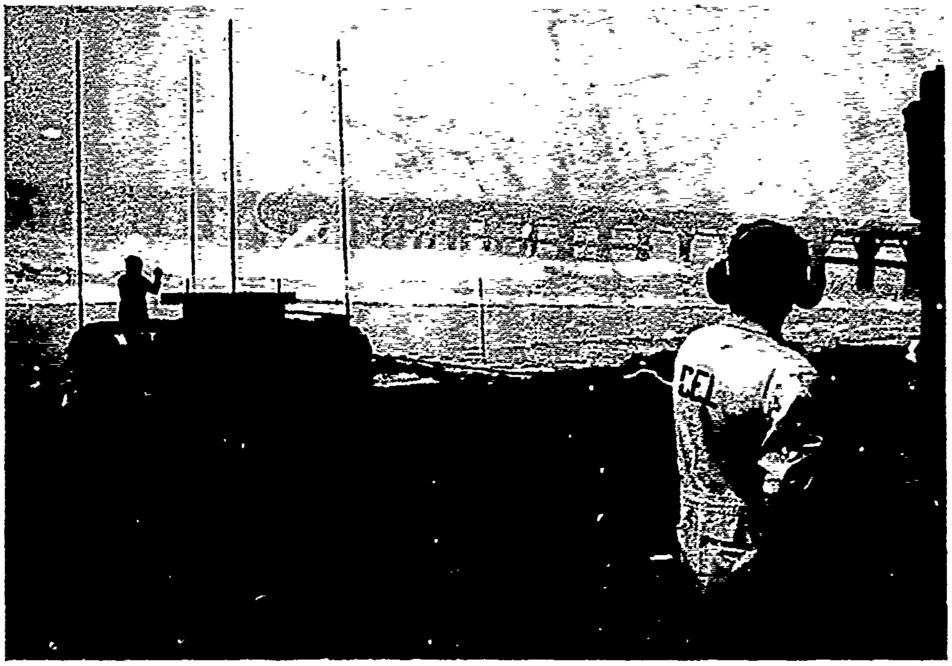
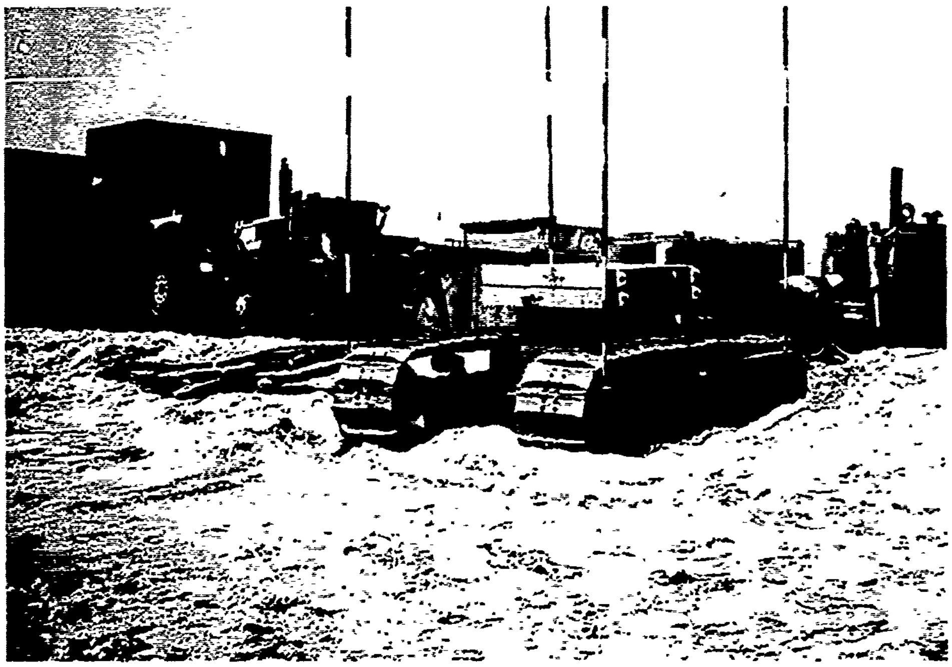


Figure 3. Portion of Pacific Missile Test Center that includes locations of STV test sites 1 and 2 (adapted from map of State of California, Point Mugu Quadrangle, prepared by U. S. Geological Survey)

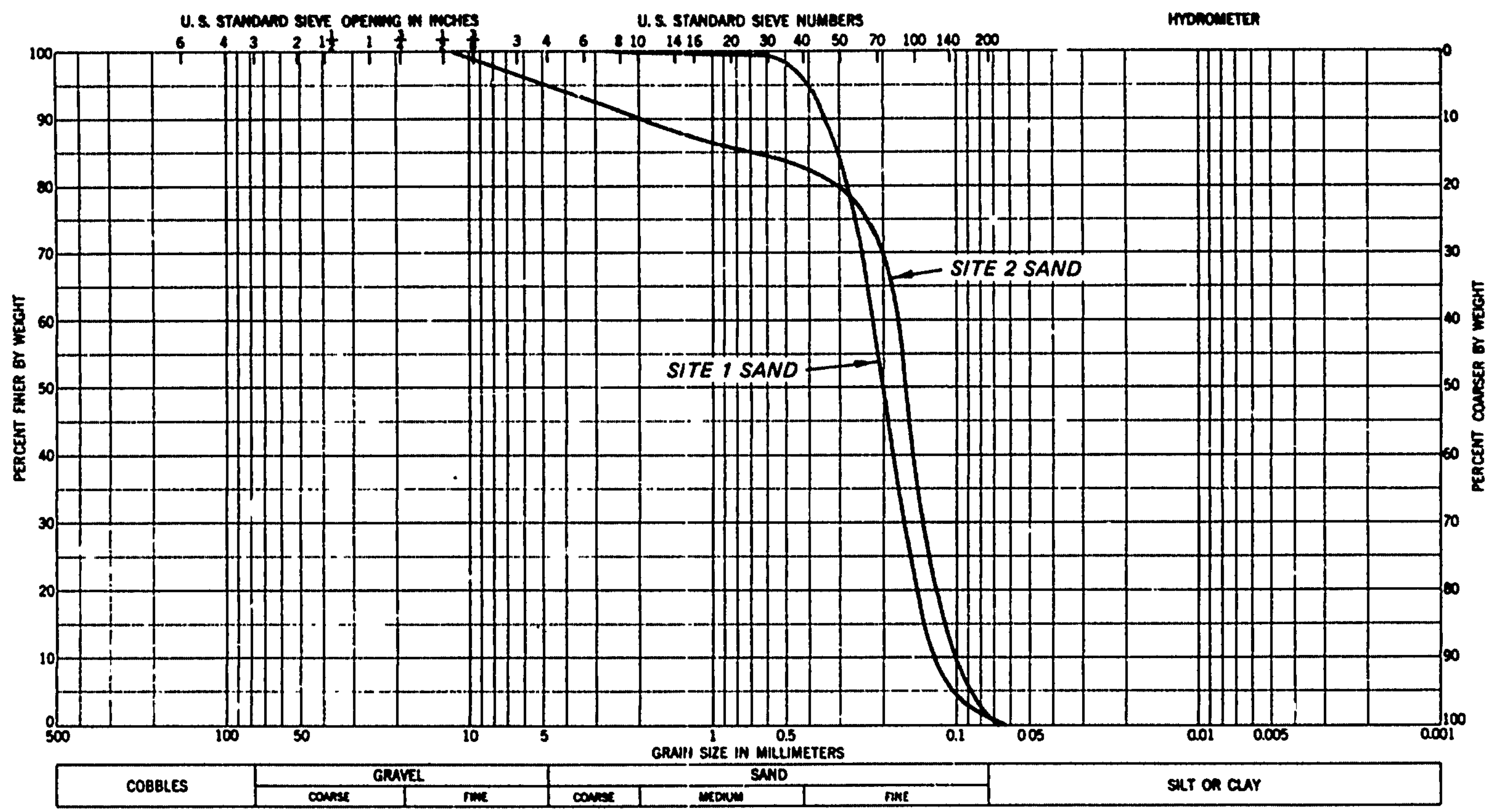


a. STV at test site 1



b. STV at test site 2

Figure 4. STV being tested



SOIL	SPECIFIC GRAVITY	DRY UNIT WEIGHT, LB/FT^3		VOID RATIO	
		MIN	MAX	MIN	MAX
SITE 1 SAND	2.69	85.5	101.2	0.659	0.963
SITE 2 SAND	2.67	90.0	103.5	0.610	0.851

Figure 5. Gradation and soil property data for sands at STV test sites 1 and 2

and 2).* Sites 1 and 2 also met the operational requirement of having access to a power supply for servicing the electronic equipment used to monitor and record STV test performance.

Conduct of Tests

Test measurements

15. Pretest measurements. Before operating the STV in a given test, measurements were taken of those STAM-required parameters necessary to describe the STV's physical characteristics and its operational environment. Relative to the STV's physical characteristics, the only on-site parameter that had to be noted was STV deadweight payload (either 0, 5,400, or 10,400 lb). Values of all the STAM-required STV physical characteristics associated with these payloads were determined well before STV testing began. These characteristics were discussed in paragraphs 6-11, and their values are listed in Table 1.

16. Pretest measurements also were made of the several environmental parameters required by STAM. The following tabulation lists these parameters, together with comments on how each parameter was measured:

a. Type of beach or seafloor material. At each of test sites 1 and 2, bulk samples of material were taken from three locations in the vicinity where the STV tests were subsequently conducted. Average results of tests on these samples are summarized in Figure 5. Evaluation of these results led to the choice of STAM relations for coarse-grained soils in describing STV trafficability performance.

b. Strength of beach or seafloor material. Before each STV test, the straight-line path that the STV would follow during testing was determined. Depending on the length of the test path (tests on or parallel to the

---

* In the STV test program, subsequent measurements of slope and cone index produced a few values outside the ranges of values measured during site selection. None of the during-test slope values were large enough or cone index values small enough, however, to cause serious problems either in conducting the STV tests or in analyzing the test results.

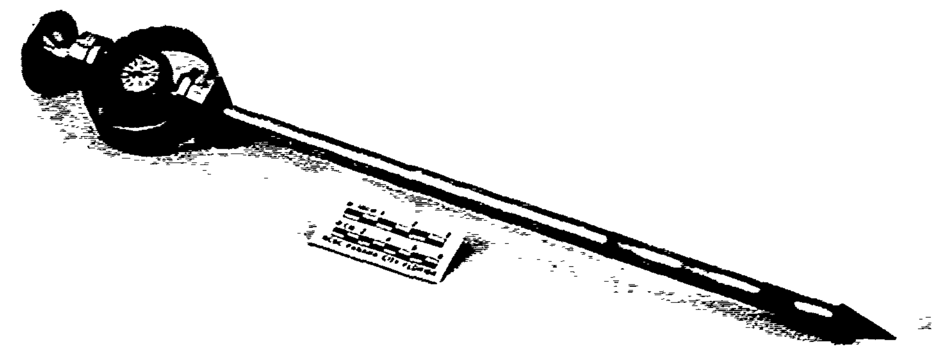
beach usually were conducted over a distance of approximately 50 to 75 ft, those from near the shoreline out into the ocean over distances of about 175 to 225 ft), measurements of cone index were taken at from two to five locations spaced fairly equally over the test path length.* In compliance with the recommendations by Howard et.al.,** five cone index penetrations were made within a radius of about 3 ft at each location to ensure that the average value of cone index obtained at that location did not deviate significantly from the value that would be obtained if a much larger number of penetrations were made. The measure of soil strength reported for each location is average cone index within the 0- to 6-in. soil layer CI_{0-6}, based on average values from the five penetrations.

Cone index penetrations in dry sand, in moist sand, and in sand covered by water up to about 2 ft deep were made by STV test personnel using a cone penetrometer modified especially for beach and nearshore trafficability measurements by the Naval Coastal Systems Center (NCSC).** Values of cone index at water depths greater than about two feet were obtained by Navy divers using an "add-weight" cone penetrometer. Figure 6 illustrates these two penetrometers, along with the standard WES cone penetrometer. The NCSC penetrometer differs from the standard penetrometer primarily in that it features (1) a waterproof housing that protects the penetrometer's force measuring micrometer and (2) a see-through plastic window that allows dial readings of cone index to be viewed when the penetrometer is used underwater. Use of the add-weight penetrometer differs from that of the standard and the NCSC penetrometers in that, instead of the user manually exerting a steady downward force on the knob at the top of the penetrometer and recording cone index values at specified increments of cone penetration depth, the penetrometer user adds incremental deadweights

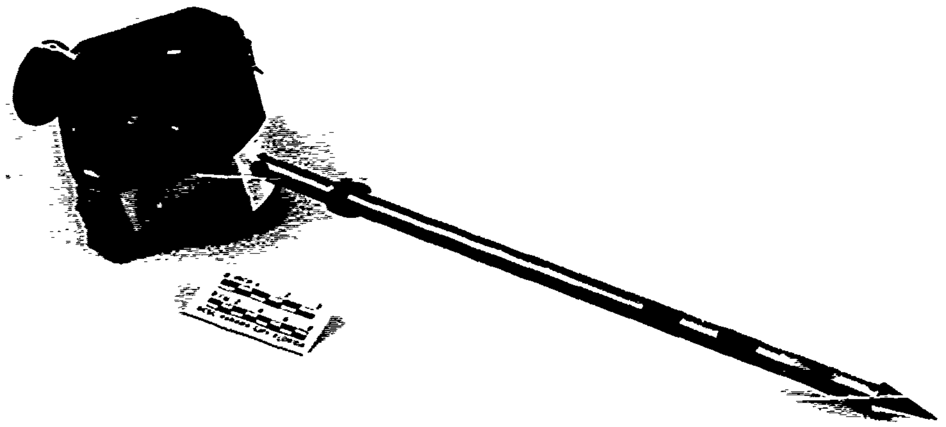
---

* For each STV test conducted parallel to the beach, all cone index measurements were made just prior to testing. For each STV test conducted from the shoreline into the ocean, measurements of cone index in sand covered by water up to about 2 ft deep were made just prior to testing; these measurements were later correlated with cone index measurements that had been made several days earlier in sand covered by water more than about 2 ft deep.

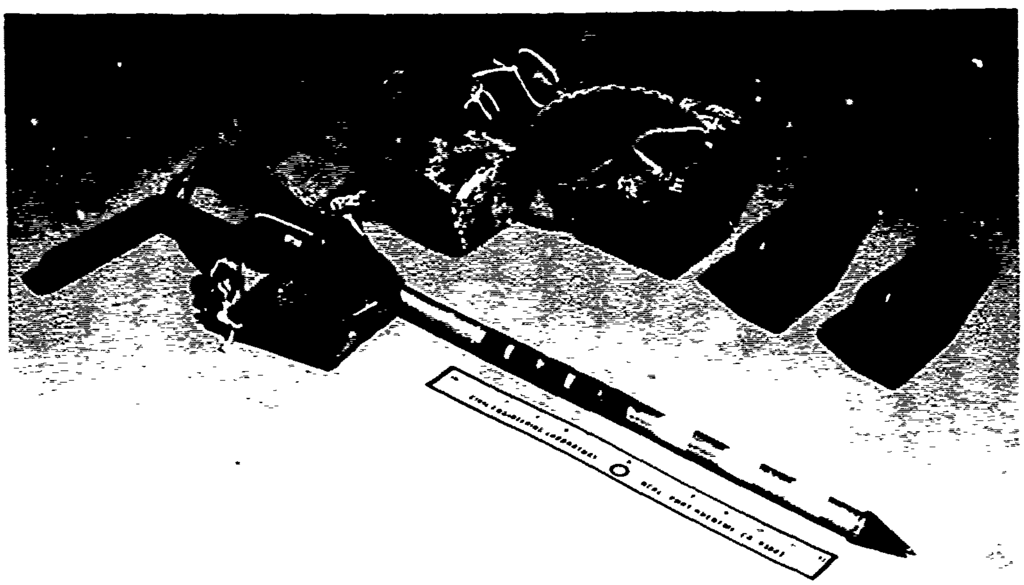
** W. W. Howard, G. G. Salsman, and C. M. Huff. 1979. "Modifying the Cone Penetrometer for Beach Trafficability Measurements," Technical Memorandum NCSC TM253-79, Naval Coastal Systems Center, Panama City, Fla.



a. Standard WES cone penetrometer



b. Naval Coastal Systems Center (NCSC) cone penetrometer



c. Add-weight cone penetrometer

Figure 6. Three variations of the cone penetrometer used to measure in-situ sand strength (adapted from photographs supplied by NCSC and CEL)

of known value to the top of the penetrometer and records the depth of cone base penetration for each amount of cumulative deadweight. (The value of cone index for each cumulative weight is known beforehand, defined simply as cumulative deadweight, in pounds, divided by cone base area, 0.5 in.^{2}) The add-weight penetrometer was much easier to use than the NCSC penetrometer in relatively deepwater situations because the user could take his time in recording cone base depth after a given incremental weight was added. In contrast, the user of of the NSCS penetrometer had little time to record cone index at particular cone base depths during a constant-speed penetration test. CEL comparisons of cone index measurements obtained with the standard, NCSC, and add-weight penetrometers at common sandy beach and nearshore locations showed that all three penetrometers (which had the same size cones and shafts) produced essentially the same results.

c. Beach or seafloor slope. Fairly extensive rod-and-level measurements of ground slope were taken during the site selection process in the areas where the site 1 and site 2 STV tests were subsequently conducted. These measurements indicated general slope values no larger than about 3 percent at site 1 and about 8 percent at site 2. Because considerable time and cost were involved in taking rod-and-level measurements in the water-covered nearshore region, measurements of ground slope were not taken just prior to each STV test. Reasonably precise estimates of beach or seafloor slope were obtained for each STV test path from during-test measurements taken with a tiltmeter mounted on the STV (described subsequently under e in paragraph 17) and from videotape recordings of the STV tests (described in paragraph 18). These estimates of slope assumed near-constant, small values of STV sinkage during a given test, an assumption supported by during-test observations. Also, for those few tests at site 2 where it was known that the STV would crawl over a significant offshore shelf, rod-and-level measurements of seafloor elevation were taken during testing.

d. Obstacle geometry, size, spacing, and location. Except for the offshore shelf mentioned above, no significant obstacles (i.e., rocks, reefs, sizeable rises or depressions in the beach or seafloor, etc.) were encountered at test sites 1 and 2.

e. Longshore current and breaker characteristics. Drift markers (floats) and a stopwatch were used to take pretest measurements of the longshore current. For the

breaking wave zone, breaking wave period was measured by stopwatch, and several other breaker characteristics were estimated or determined visually--breaker height, breaking wave angle to the shoreline, breaker location and width, and breaker type (plunging, spilling, or collapsing). (These pretest determinations were supplemented by examination of videotape recordings of the STV tests conducted out into the ocean.)

17. During-test measurements. During a given STV test, continuous analog recordings were made on magnetic tape of measurements of a number of test control and STV performance parameters. These parameters are listed below, together with comments on how each parameter was measured:

a. Drawbar pull (DBP). A 30,000-lb capacity electronic load cell was mounted at the STV end of a steel cable that connected the rear of the STV and a winch unit that was anchored on the beach. The load cell measured STV drawbar pull, which included not only the controlled reaction force applied by the winch, but also the force required to pull the bundled instrumentation and hydraulic lines that were tied to the steel cable behind the STV for a given test. (The winch system was somewhat insensitive, so that the winch operator could not react quickly in applying a variable amount of reaction force to meet fast-changing test conditions. This situation produced only a few suspicious drawbar pull test data, however, that are discussed in detail in paragraph 50.)

b. STV track speed (T). This parameter was measured indirectly for each track by first establishing the linear correlation between track speed and hydraulic flow rate in the return line from the STV motor, at the onshore pump (one correlation per track).* Flow rates for the two lines were continuously measured during each test by flowmeters, and these rates were later converted to track speeds. The value reported herein is the average of STV left and right track speeds, or STV (average) track speed, T .

c. STV vehicle speed (V). A specially fabricated steel sheave and idler wheel with grooved 1-ft circumferences was positioned within a frame that, during STV testing,

* Direct measurement of track speed was abandoned because of lack of a physical location for placing a transducer to sense movement of the gear teeth of the STV's drive sprocket. Also, there was not available at the time of testing a tachometer capable of measuring the lowest track speed tested, 10 ft/min.

was anchored on the beach near the winch that was used to apply a controlled reaction force to the STV. A spring in the frame caused the steel cable that emanated from the winch to be clamped firmly between the sheave and the idler wheel. A transducer attached to the idler wheel produced an electrical signal of 2000 pulses per wheel revolution (or per one foot of cable and STV travel). This signal was recorded as a frequency (i.e., pulses per second) that was subsequently converted to an analog and then to a digital signal during the STV data reduction rocess. (A recorded frequency of 1000 pulses/sec, for example, converted to 0.50 ft/sec, or 30 ft/min STV vehicle speed V .)

d. Hydraulic horsepower input (HYDHP). Measurements of hydraulic pressure differential at the onshore pumps (one measurement per track) were incorporated with measurements of hydraulic flow rate in the return lines to the pumps (the same measurement described in item b above—again, one measurement per track) to produce an indirect measurement of HYDHP , hydraulic horsepower input by the onshore pumps to the STV/hydraulic lines system. STAM does not predict HYDHP . This parameter was measured for the STV tests, however, because of CEL interest in power supply considerations for remotely powered and controlled bottom-crawling vehicles in general and for the STV in particular. In keeping with this interest, Appendix A describes some considerations relative to power input and power efficiency.

e. STV pitch angle. A tiltmeter, accurate to ±1 deg and mounted near the front of the STV on the vehicle center line, measured STV pitch angle.

f. Time code. This channel recorded time to the nearest second (i.e., IRIG time in units of month, day, hour, minute, second).

g. Voice. This channel was used to record comments appropriate to a detailed description of individual STV tests.

18. It was initially planned to take analog measurements of STV water depth by means of two pressure cells, one mounted near each end of the STV. Only one such cell was available at the time of testing, however, and it was determined early in testing that this cell's readings were unreliable. Videotape recordings were made of STV tests conducted out into the ocean, however. From observations of the 1-ft interval marks on the four vertical rods shown in Figure 1, it was possible to obtain a reasonably accurate estimate of water depth at a given STV

location. (The analog and videotape records of a given STV test were coordinated by means of voice signals made on both records at key times during the test.) In additon to visually portraying the general progression of a given STV test, the videotape records could also be analyzed to provide descriptions of the seafloor (in terms of slope, water depth, and obstacles) and the sea state (in terms of longshore current and breaker characteristics).

19. Finally, in addition to the analog and videotape records of the STV tests, an oscillograph record was made during each test of several key STV control and performance parameters (STV drawbar pull, STV track and vehicle speeds, and STV pitch angle being the most important ones). Values of these parameters were monitored during and just after each test to determine whether a given STV test appeared to be valid. During-test data reported herein were obtained from a coordinated analysis of all three types of during-test records—analog, videotape, and oscillograph.

Test procedures and controls

20. Test procedures and controls varied primarily according to which of the two types of STV test was being conducted, a variable slip test or a constant slip test. For each type test, STV slips S, in percent, equals $\frac{T - V}{T} \times 100$, where T is STV track speed and V is STV vehicle speed.

21. Variable slip tests. The procedure followed in conducting a given one-pass, variable slip test was as follows:

a. Select the values of the test control variables (given in paragraph 22) and the straight-line STV test path. Position the test support equipment properly relative to the STV and move the STV to the start position on the test path. For example, the sketch in Figure 7 illustrates the arrangment of equipment for an STV test to be conducted parallel to and landward of a berm crest.

b. Take appropriate pretest measurements (described in paragraph 15). Calibrate instrumentation for the during-test measurements described in paragraph 17.

c. Starting with a small amount of slack in the steel cable between the winch and the STV, move the STV forward at constant track speed T throughout the test (where

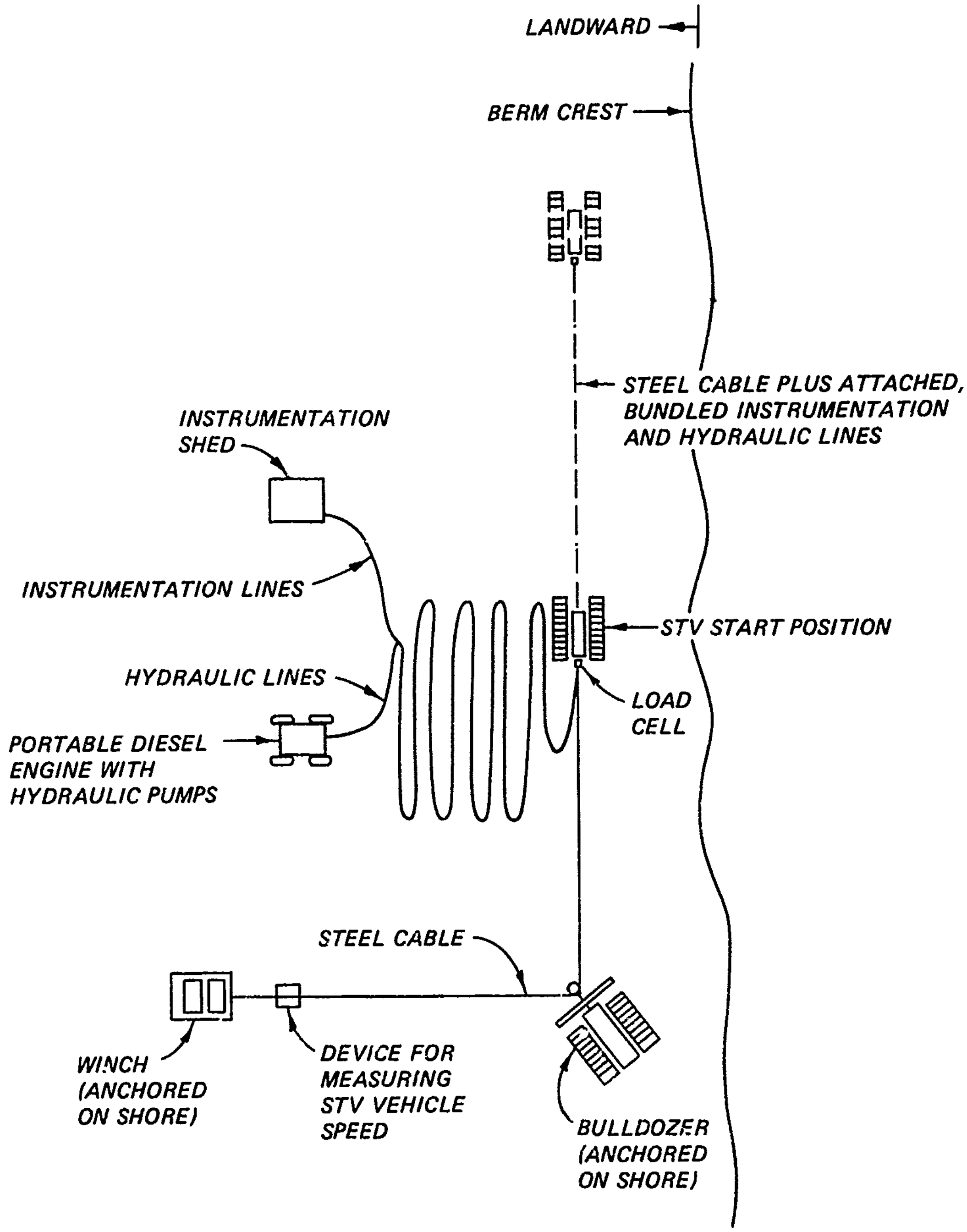


Figure 7. Arrangment of equipment for STV tests conducted parallel to and landward of berm crest

values of T are presented in paragraph 22). Over the full length of the test, uniformly increase the reaction force in the cable (i.e., uniformly increase the braking effort at the winch), thereby causing (1) STV slip to increase from a small to a large positive value and (2) STV drawbar pull to increase from zero to a value large enough to prevent further forward motion of the STV. Continuously record all during-test measurements.

22. Variable slip tests were conducted at site 1 in three types of locations: in dry sand with the STV a short distance landward of and roughly parallel to a berm crest located about 50 ft from the water's edge; in moist (but not water-covered) sand with the STV seaward of and roughly parallel to the berm crest; and in submerged sand covered by shallow water with the STV at a slight angle to and near the shoreline. The primary purpose of the variable slip tests was to generate data for determining the characteristic shape or shapes of the drawbar pull versus slip curve for the STV over a range of gross vehicle weights (12,250 to 22,650 lb) and track speeds (12.5 to 37.5 ft/min) in dry, moist, and submerged sand. To accomplish this, the variable slip tests were conducted under the following controls:

Test No.	Sand Condition	STV Gross Vehicle Weight, lb	Nominal STV Track Speed T, ft/min*
1	Dry	22,650	12.5
2	Dry	22,650	25.0
3	Dry	22,650	37.5
4	Moist	12,250	12.5
5	Moist	12,250	37.5
6	Moist	22,650	12.5
7	Moist	22,650	37.5
8	Submerged	12.250	12.5
9	Submerged	12,250	37.5
10	Submerged	22,650	12.5
11	Submerged	22,650	37.5

* Maintaining track speed T constant (paragraph 21) at either 12.5, 25.0, or 37.5 ft/min while causing vehicle speed V to decrease from its initial value to zero caused 20 percent slip to be reached at V values of 10, 20, and 30 ft/min, respectively. These T and V test control values were established because (a) 20 percent was the nominal slip value anticipated to represent a good balance between achievable drawbar pull and reduction in vehicle speed due to slip and (b) 10, 20, and 30 ft/min were the intended values of V for subsequent constant slip tests.

23. Constant slip tests. It is important to contrast the basic differences between the variable slip tests and the constant slip tests in terms of the environmental and test control conditions associated with each type of test. Each variable slip test was conducted either on or near the beach under near-constant values of all important environmental parameters so that, for analysis purposes, it was possible to determine the effect of STV slip on drawbar pull performance free of the influence of variations in environmental conditions. However, for each test conducted by crawling the STV from the beach out into the Pacific Ocean, the values of key environmental parameters associated with water depth and seabottom conditions changed significantly during the test. For each of these tests, it was desirable for analysis purposes to hold the values of all other control variables constant, including STV slip.

24. Onsite analysis of results from the variable slip tests confirmed that 20 percent was a reasonable nominal slip value to approximate the field condition at which optimum STV drawbar pull performance is obtained. (A detailed analysis of the STV variable slip test results is described in paragraphs 27-41.) The procedure used in conducting a given one-pass constant 20 percent slip test was as follows:

a. Select the values of the test control variables (given in paragraph 26) and the straight-line STV test path. Position the test support equipment properly relative to the STV and move the STV to the start position on the test path. For example, a sketch of equipment arrangement for an STV test perpendicular to the shoreline would be the same as that in Figure 7 except for orientation of the STV and its test support equipment relative to the shoreline.

b. Take pretest measurements. Calibrate instrumentation for during-test measurements.

c. Move the STV forward at constant track speed $T = 1.25V$ (where values of V appear in paragraph 26). Apply sufficient reaction force at the winch to cause track vehicle speed V to remain constant at its preselected value. Continue the test unitl the full length of bundled hydraulic and instrumentation lines attached to the steel cable are payed out. Continuously record all during-test measurements.

25. Each constant slip test began with the STV in moist sand a few feet landward of the water's edge and continued as the STV crawled along a straight line into the Pacific. For successive tests conducted on the same day at the same general location,* the start positions of adjacent STV test paths were separated by a distance of about 15 ft. One test path was perpendicular to the shoreline, and the adjacent path on either side followed a straight line that moved away from the perpendicular by about 20 deg as the adjacent path progressed oceanward.

26. Constant 20 percent slip tests were conducted with the STV at both test sites 1 and 2 over the same ranges of gross vehicle weights and STV vehicle speeds (i.e., V values at 20 percent slip) that were used in the variable slip tests (12,250 to 22,650 lb and 10 to 30 ft/min, respectively). The test controls used were:

Site No.	Test No.	STV Gross Vehicle Weight, lb	Nominal STV Vehicle Speed V, ft/min
1	12	12,250	10
	13	12,250	20
	14	12,250	30
	15	17,650	10
	16	17,650	20
	17	17,650	30
	18	22,650	10
	19	22,650	20
	20	22,650	30
2	21	12,250	10
	22	12,250	30
	23	22,650	10
	24	22,650	30

* Two locations were used at site 1 (near stations 200 and 250 ft southeast of the large pier), and one location was used at site 2 (near a station about 240 ft east of Jet Engine Test Building 731).

PART III: ANALYSIS OF TEST RESULTS

Variable Slip Tests

Listing of test results

27. Results of the STV variable slip tests are summarized in Table 2. The ordering of tests and the test control conditions in Table 2 are the same as summarized earlier in paragraph 21. Columns 2 to 7 in Table 2 list those parameters whose values remained constant or near-constant during STV testing--i.e., the test control parameters. Columns 8 and 9 list values of STV pitch angle and hydraulic horsepower input, respectively, two parameters of secondary interest herein. Column 10 lists CI_{0-6} , the average 0- to 6-in. cone index value of each group of five cone index penetrations made within a 3-ft radius at either two or three locations within the 50- to 75-ft length of each STV test path. Figure 8 illustrates interpretation of the five cone index penetrations that produced the first CI_{0-6} value for Test No. 9 in Table 2, for example. For each test, the number in parentheses in column 10 is the average of that test's two or three CI_{0-6} values; this average CI_{0-6} value is used subsequently herein to describe the sand strength of the overall test path. In Table 2, average CI_{0-6} values ranged from 38 to 96. Finally, columns 11 to 14 list the changing values of parameters descriptive of the STV's drawbar pull performance during each variable slip test. Because all STV tests in Table 2 were conducted at site 1 where ground slope values were small (never larger than 3 percent within a given 30-ft distance of STV test path), drawbar pull values in Table 2 were not corrected for ground slope. Also, because water depth was never greater than a few inches in the submerged variable slip tests, vehicle weight was characterized as in-air gross vehicle weight GVW for all variable slip tests--dry, moist, and submerged.

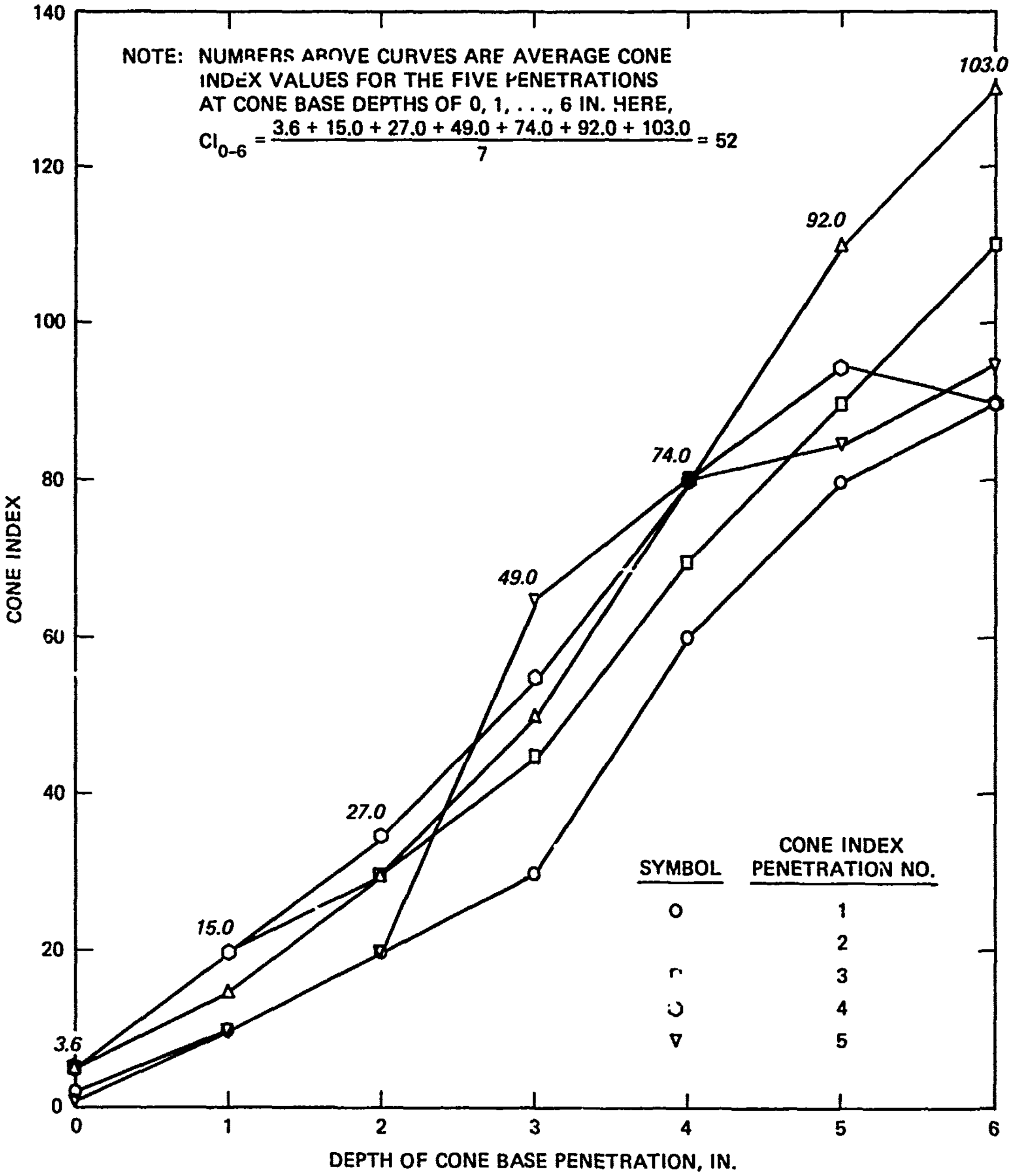


Figure 8. Computation of first CI_{0-6} value of Test No. 9 based on interpretation of five cone index penetrations

Influence of test
control variables

28. The next several paragraphs describe the influence on STV drawbar pull performance in the variable slip tests caused by the three principal test control variables used--STV track speed, STV gross vehicle weight, and sand wetness condition. Relative to the influence of track speed T , Figure 9 illustrates the relation of pull coefficient (drawbar pull/gross vehicle weight) versus slip produced by STV variable slip tests at one gross vehicle weight (22,650 lb) and one sand wetness

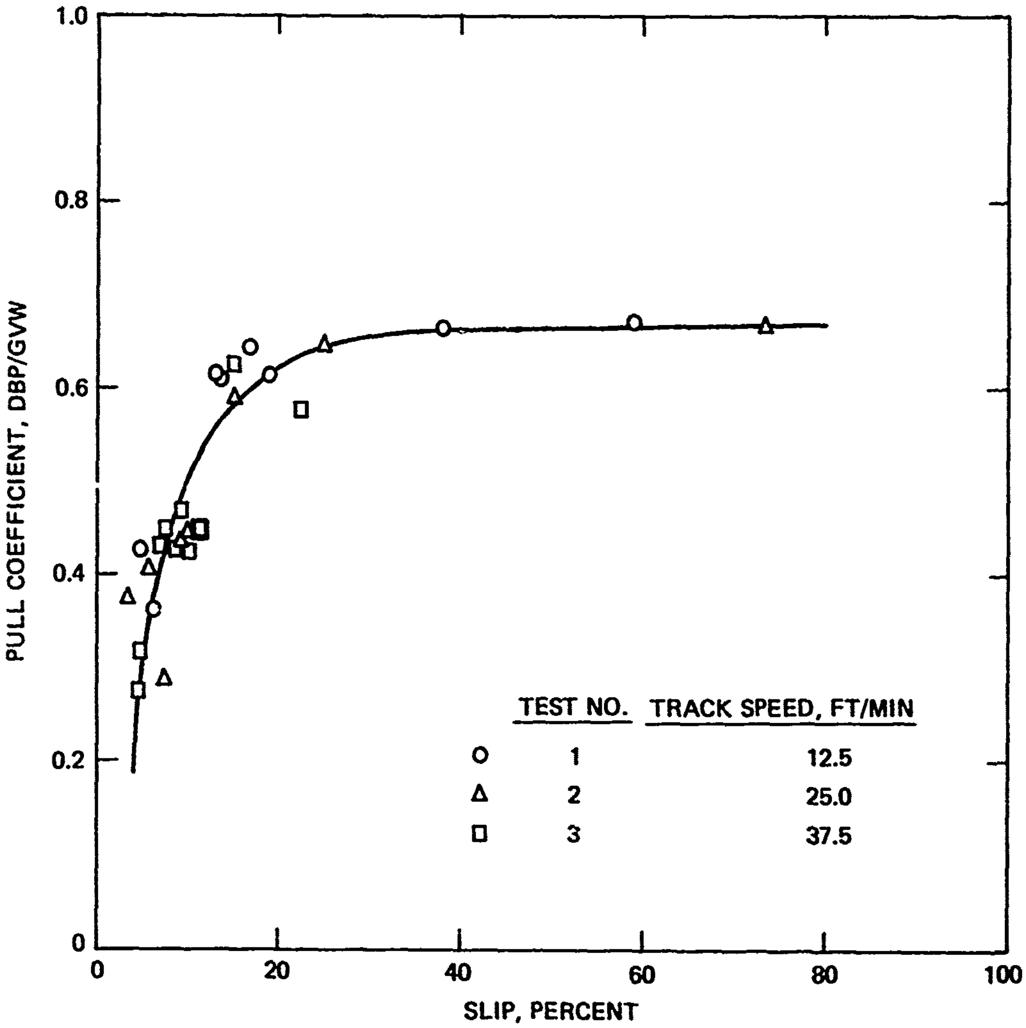


Figure 9. Relations of pull coefficient to slip for STV tests conducted in dry sand at track speeds of 12.5, 25.0, and 37.5 ft/min

condition (dry sand) at T values of 12.5, 25.0; and 37.5 ft/min. The single curve in Figure 9 reasonably describes the relation defined by the test data, indicating that for T values from 12.5 to 37.5 ft/min, track speed had negligible influence on the pull coefficient versus slip relation in a typical dry beach sand (with STV gross vehicle weight GVW held constant).

29. The relations of pull coefficient to slip for STV tests conducted in moist sand and in sand submerged by shallow water are illustrated in Figures 10 and 11, respectively. Part a in each figure describes results of STV tests with GVW = 12,250 lb , and part b describes results with GVW = 22,650 lb . In both parts a and b of Figures 10 and 11, test data are presented for two STV track speeds, T = 12.5 and 37.5 ft/min .

30. For each combination of sand wetness condition, STV track speed, and STV gross vehicle weight illustrated in Figures 10 and 11, the relation of pull coefficient to slip is described reasonably well by the same curve that was used in Figure 9 for STV performance in dry sand. Two major considerations contributed to this result.

31. First, since Figure 9 showed that the pull coefficient versus slip relation for STV tests in dry sand was essentially uninfluenced by track speeds from 12.5 to 37.5 ft/min, it was speculated that the same relation for STV tests in moist and in submerged sand would also not be influenced by the same range of T values. Results in parts a and b of each of Figures 10 and 11 confirm this speculation.

32. Secondly, considerable test experience in dry sand has shown that, for a given tracked vehicle and gross vehicle weight, if sand strength is great enough to allow the vehicle to develop nearly its maximum attainable value of pull coefficient (somewhat larger than 0.6) at large values of slip (say, 20 percent or larger), then the vehicle's pull coefficient versus slip curve is nearly the same as the curve that would be obtained for all other soil strength/GVW combinations that permit near-maximum pull coefficient. It does not seem unreasonable that this same type of limiting condition should prevail for tracked vehicle performance in moist and in submerged sand. Thus, it was not

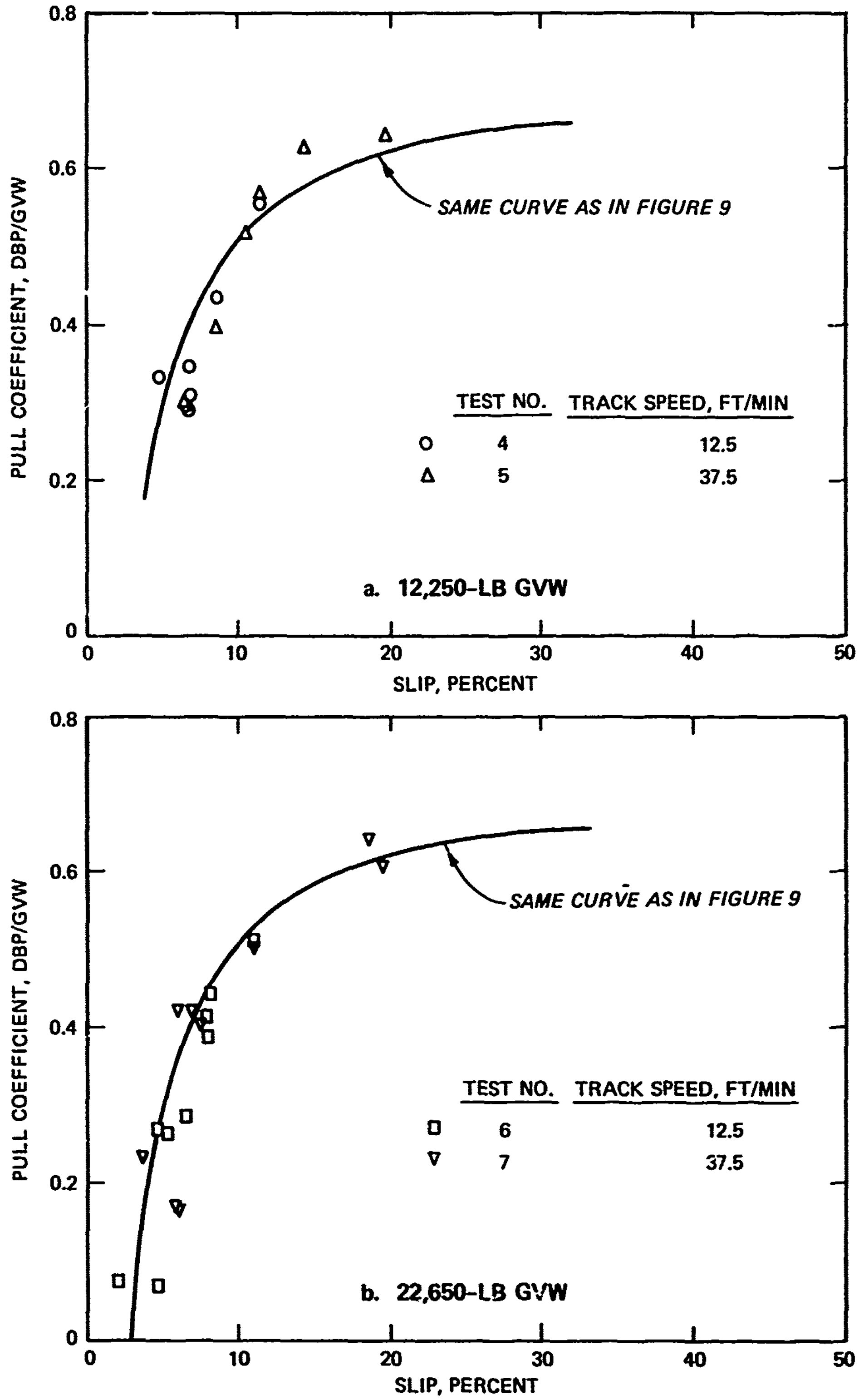


Figure 10. Relation of pull coefficient to slip for STV tests conducted in moist sand at two gross vehicle weights and two track speeds

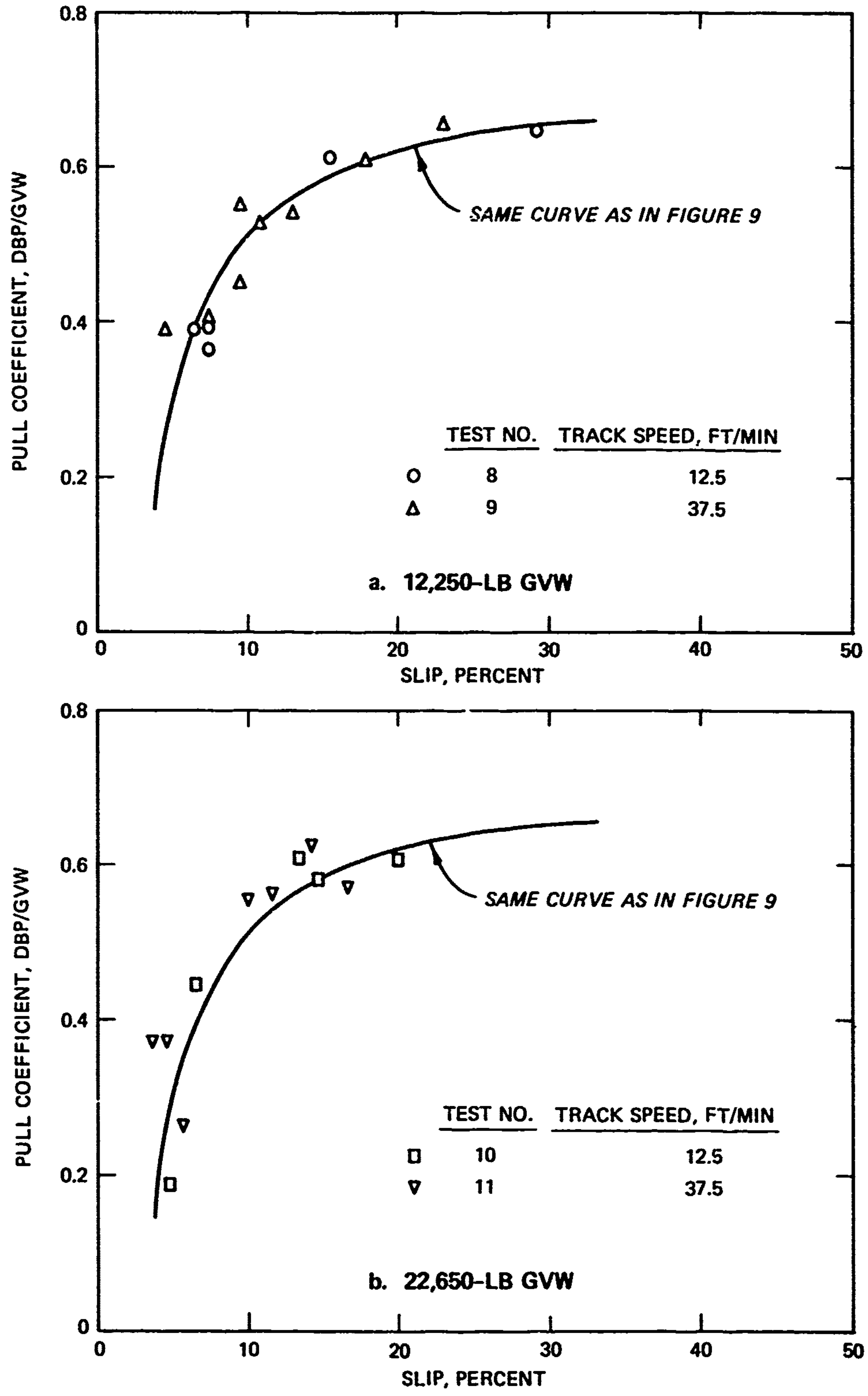


Figure 11. Relation of pull coefficient to slip for STV tests conducted in submerged sand at two gross vehicle weights and two track speeds

surprising that in Figures 10 and 11, the same curve can be used to describe the pull coefficient versus slip relation for both the 12,250-lb and the 22,650-lb gross vehicle weight conditions (part a versus part b in each of these figures) over a range of sand strength (average CI_{0-6}) values.

33. In connection with this second consideration (in paragraph 32), it is useful to define in quantitative fashion the limiting condition beyond which continued increases in sand strength produce negligible increases in tracked vehicle pull coefficient. Based on analysis of results from a large number of laboratory tests conducted in two dry sands with a versatile model track running gear, Turnage* developed the relation shown in Figure 12. The ordinate term in Figure 12 is DBP_{20}/GVW , pull coefficient at 20 percent slip, and the abscissa term is N_s , the sand-track mobility number, a dimensionless vehicle performance prediction term defined as

$$N_s = \frac{G(TW \times TLC)^{1.5}}{0.5\ GVW} \left(\frac{GVW}{GVW_t}\right)^{0.5} \left(\frac{d}{TLC/2}\right)^{n} \quad (1)$$

where

G = the average gradient, or slope, of the cone index versus penetration depth curve within the 0- to 6-in. sand depth, $lb/in.^3$

TW = track width, in.

TLC = track length in contact with ground (on a hard surface), in.

GVW = in-air gross vehicle weight, lb

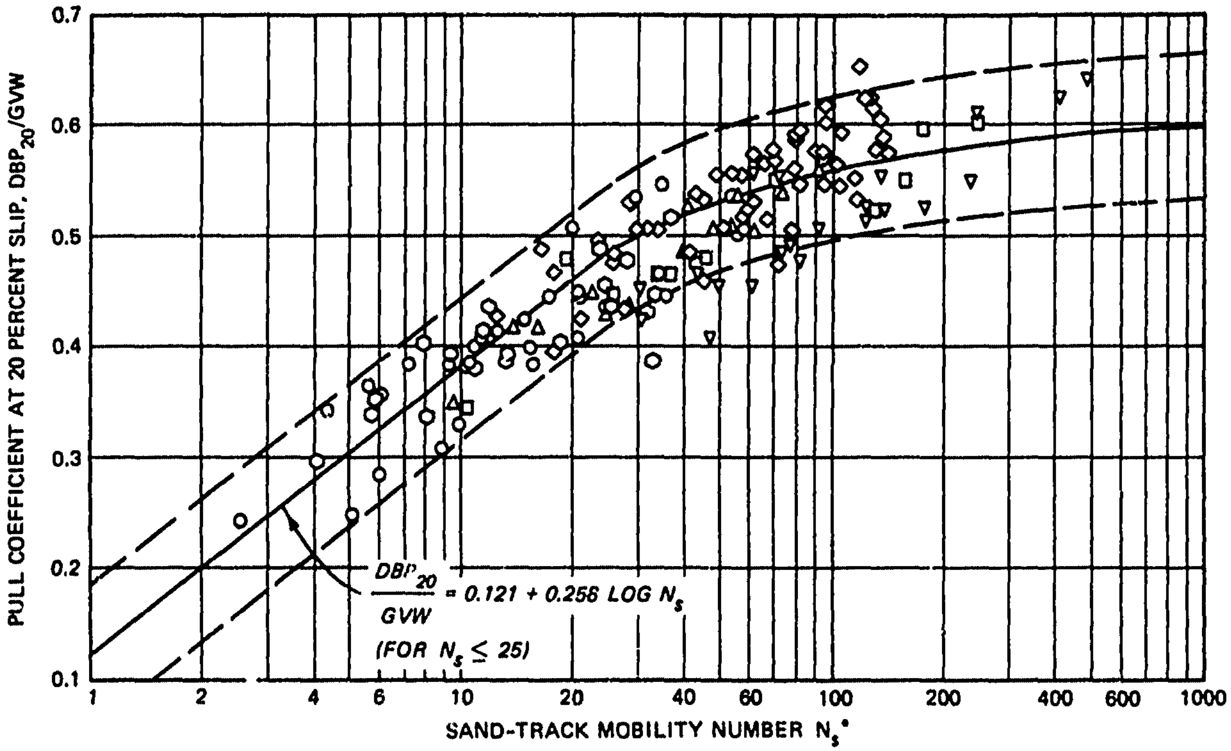
GVW_t = in-air gross vehicle weight that causes maximum deflection of the road bogies (i.e., causes the road bogies to "bottom out"), lb.

d = distance from the center of the vehicle's rear road wheel to a vertical line through the vehicle's center of gravity, in.

n = 0.5 for d < TLC/2; 1 for d = TLC/2; and 3/2 for d > TLC/2

---

* G. W. Turnage, 1976. "Performance of Soils Under Track Loads; Track Mobility Number for Coarse-Grained Soils," Technical Report M-71-5, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.



$$^{*}N_s = \frac{G(TW \times TLC)^{1.5}}{0.5\ GVW} \cdot \left(\frac{GVW}{GVW_t}\right)^{0.5} \cdot \left(\frac{d}{TLC/2}\right)^{n} \quad \text{IN DRY SAND}$$

$$= \frac{CI_{0-6}(TW \times TLC)^{1.5}}{1.75\ GVW}$$

FOR CONDITIONS OF THE STV VARIABLE SLIP TESTS (WHERE IN-AIR GVW WAS THE APPROPRIATE MEASURE OF STV WEIGHT)

LEGEND

	TW, IN.	TLC, IN.
○	6	24
△	12	24
□	24	24
○	6	48
◇	12	48
▽	24	48

Figure 12. Relation of pull coefficient at 20 percent slip to sand-track mobility number N_s (based on laboratory tests of model tracks in two dry sands, adapted from Turnage (1976))

34. In relating N_s to the STV test results, consider first that for each of the two types of dry sand used in the tests reported,* G values could be converted to values of average cone index in the 0- to 6-in. soil layer (i.e., to values of CI_{0-6}) by the relation

$$CI_{0-6} = 3.5G \tag{2}$$

The gradation and soil property data for the site 1 and site 2 sands in Figure 5 had values generally within the range of values of corresponding data for the two sands.* Thus, it should be permissible to use Equation 2 for the site 1 and site 2 sands. Secondly, note for a tracked vehicle with rigid (girderized) suspension like that of the STV, the value of $\frac{GVW}{GVW_t}$ in N_s can be taken as 1.0. Finally, for a tracked vehicle with its center of gravity near its longitudinal center line (like the STV), the value of $\left(\frac{d}{TLC/2}\right)^n$ in N_s can also be taken as 1.0. For the STV, then, N_s is closely approximated by

$$N_s = \frac{CI_{0-6} \, (TW \times TLC)^{1.5}}{1.75 \; GVW} \tag{3}$$

35. In Figure 12, values of DBP_{20}/GVW increase only slightly as values of N_s increase beyond about 100. For the eleven STV tests whose results are illustrated in Figures 9, 10, and 11, values of N_s (as defined by Equation 3) ranged from 182 to 718. Thus, if the relation in Figure 12 is applicable not only for dry sands, but also for moist and for submerged sands, then it should be expected that the value of pull coefficient at 20 percent slip would be about 0.6 for all test conditions included in Figures 9, 10, and 11. The test results do not contradict this speculation.

36. In summary, for the range of STV track speeds and gross vehicle weights tested and for the sand strengths and sand wetness conditions involved, a single curve (as in Figure 9) appears adequate to

---

* Turnage, op. cit., p 33.

describe the STV's pull coefficient versus slip relation. This result was produced primarily by the negligible influence on test results of the fairly narrow range of low track speeds tested (12.5 to 37.5 ft/min); by sand strengths great enough to allow the STV to develop near-maximum pull performance for the two STV gross vehicle weights tested (12,250 and 22,650 lb); and by the apparently small influence of the three sand wetness conditions (dry, moist, and submerged) on STV pull performance.

37. While the above results are straightforward, one should be cautious in extrapolating these results far beyond the range of test conditions under which they were obtained. First, it is possible that track speed might influence tracked vehicle pull performance for speeds far less than 12.5 ft/min or far greater than 37.5 ft/min. For track speeds reasonably close to the range from 12.5 to 37.5 ft/min, however, it is anticipated that speed will have little influence on tracked vehicle pull. Second, for all three sand wetness conditions tested--dry, moist, and submerged--it is expected that the combination of tracked vehicle gross vehicle weight and sand strength that will allow a given tracked vehicle to attain near-maximum pull is defined by an N_s value of about 100 or larger. Results of the STV variable slip tests described to this point are complemented by results of the constant slip tests described later in this report, particularly with regard to application of a relation like that in Figure 12.

Shape of the pull coefficient versus slip curve

38. One of the principal reasons for conducting the variable slip tests was to analyze the shape (or shapes) of the pull coefficient versus slip curves obtained to determine the appropriate slip value to use in the subsequent constant slip tests. The exact shape of the pull coefficient versus slip curve for a tracked vehicle in dry sand changes as a function primarily of sand strength, vehicle load, and several vehicle physical characteristics (but principally the size of the vehicle's tracked running gear)--i.e., primarily as a function of the variables in sand-track mobility number N_s . Measurements taken during the site selection process at both the site 1 and the site 2 constant

slip test areas indicated that roughly the same ranges of cone index values would be encountered for the constant slip tests as were obtained in the variable slip tests. Thus, roughly the same range of N_s values would be obtained in the constant slip tests and the curve shape in Figures 9 to 11 was valid to use in selecting the value of slip to be held constant in the second test series.

39. The general characteristics of the single curve shape in Figures 9 to 11 are the same as those obtained in many field and laboratory tests of tracked vehicles in dry sand. Values of the pull coefficient first increase rapidly as slip increases from a small positive value to a value somewhat less than 20 percent. Next, the rate of increase of pull coefficient decreases markedly as slip approaches 20 percent. Finally, the coefficient increases only slightly as slip values continue to increase beyond 20 percent. On the basis of this curve shape, it was judged that a reasonable nominal value of slip to use in the constant slip tests was 20 percent.

40. This judgement is reinforced by the very important consideration of a tracked vehicle's tractive efficiency TE , defined as

$$TE = \frac{\text{Output Power}}{\text{Input Power}} \tag{4}$$

which can be expressed as

$$TE = \frac{DBP(V)}{M\omega} = \frac{DBP(V)}{M\,\frac{T}{r}} \tag{5}$$

where

V = vehicle actual translational speed

M = torque input to vehicle drive sprockets

ω = angular velocity of the drive sprockets

T = vehicle track speed = vehicle theoretical translational velocity = $r\omega$

r = drive sprocket pitch radius

In nearly any system that includes an input and an output, the efficiency with which the output is obtained is important. The efficiency with which input power is converted to output power is probably even more important for a bottom crawler operating in a relatively remote near-

shore environment than for a conventional vehicle operating in a more accessible environment because availability of input power often is much more limited in a remote environment.

41. Figure 13* illustrates the relations of pull coefficient and tractive efficiency to sand-track mobility number N_s for tracked vehicles in dry sand operating at two performance levels--at constant 20 percent slip and at the point where maximum tractive efficiency is obtained (the TE_{max} point). In the upper part of Figure 13, for all but the smallest N_s values (about 10 and under), 20 percent slip develops values of pull coefficient about 0.04 larger than does the TE_{max} condition. In the lower part of Figure 13, for values of N_s of about 40 and larger, TE_{max} has tractive efficiency values approximately 0.1 larger than those for the 20 percent slip condition. This trade-off in pull and tractive efficiency capabilities for the 20 percent slip and TE_{max} conditions confirms, again, that 20 percent was a reasonable nominal slip value for conducting the STV constant slip tests.

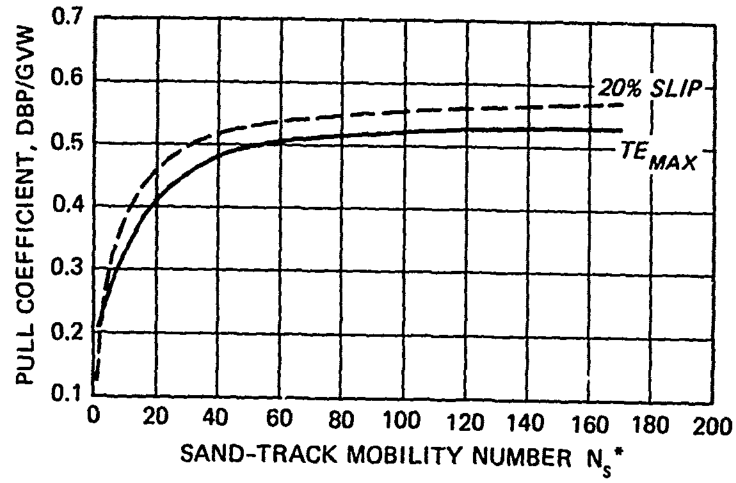
Constant Slip Tests

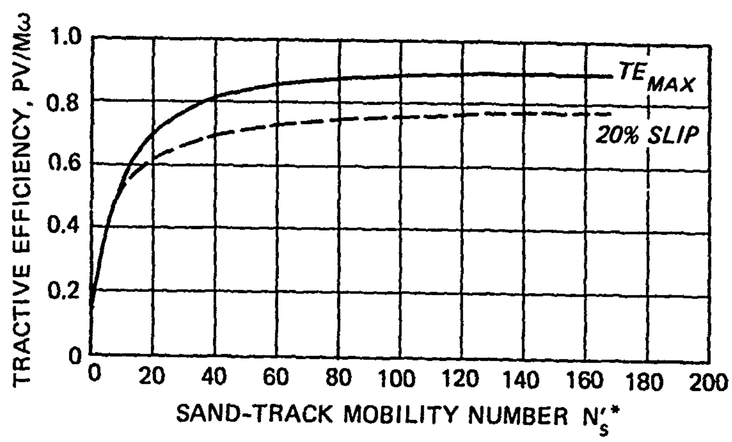
Listing of test results

42. Results of the STV constant 20 percent slip tests are summarized in Table 3. Columns 2 to 8 of the table list those parameters whose values remained constant or near-constant during a given test--i.e., test control parameters and several environmental parameters. Columns 9 and 10 list values of STV pitch angle and hydraulic horsepower input, respectively. Column 11 lists CI_{0-6} values, each one representing the average 0- to 6-in. cone index value of five cone index penetrations made within a 3-ft radius. For each test, the number in parentheses in column 11 is the average of the five CI_{0-6} values measured at locations spaced fairly equally over the length of each test

---

* Turnage, op. cit., p 33.





$$*N_s = \frac{G(TW \times TLC)^{1.5}}{0.5\ GVW} \cdot \left(\frac{GVW}{GVW_t}\right)^{0.5} \cdot \left(\frac{d}{TLC/2}\right)^n \text{ IN DRY SAND}$$

$$= \frac{CI_{0-6}\,(TW \times TLC)^{1.5}}{1.75\ GVW} \text{ FOR CONDITIONS OF THE STV VARIABLE SLIP TESTS}$$

Figure 13. Relations of pull coefficient and tractive efficiency to sand-track mobility number N_s for the 20 percent slip and maximum tractive efficiency conditions (based on laboratory tests of model tracks in two dry sands, adapted from Turnage, op.cit., p.33)

path, and is the value used subsequently herein to describe the sand strength of the overall test path. In Table 3, average CI_{0-6} values ranged from 43 to 56 (a considerably smaller range of average CI_{0-6} values than was encountered in the variable slip tests). Column 12 lists the values of STV slip measured at the specified distances from the shoreline, as listed in column 13. Columns 14 to 19 list those parameters whose values changed significantly during a given test--i.e., environmental parameters influenced by STV location relative to the shoreline and parameters associated with STV drawbar pull, the only major vehicle performance parameter measured. Finally, column 20 lists values of N_s' sand-track mobility number modified from N_s to account for vehicle buoyancy. (N_s' is described in detail in paragraph 46.) Note that, unlike any other parameter in Table 3, the approximate local slope in column 15 applies to the intervals <u>between</u> sample distances in column 13 rather than to individual sample points--e.g., for Test No. 12 the first value of local slope (1.7 percent) describes the nearshore slope within the first 30 ft from the shoreline. Column 17 lists measured values of STV drawbar pull DBP, and column 18 lists values of DBP corrected for local seafloor slope θ. This correction was made during test data reduction by subtracting from DBP the quantity VEW $\sin \theta$, that component of vehicle effective weight that adds to DBP for a vehicle moving downslope. (VEW is defined in detail in paragraph 45.) Note in columns 18 and 19 that the value of θ used in each computation is the value of θ for the preceding interval of distance from shoreline--i.e., each computation "looks back" and uses the slope of the nearest preceding interval of seafloor distance. Note, finally, that the STV test paths are described in some detail by entries in columns 2, 11, and 13 to 15 in Table 3 and by subsequent information in paragraphs 43 and 44.

43. For site 1, Table 3 lists values of parameters in columns 9, 10, 12 to 14, and 16 to 19 that were sampled at the shoreline and at 30-

ft intervals of STV travel into the ocean up to a distance of 210 ft.* For site 2, values of the same parameters were sampled at distances of 0, 10, 20, 30, 40, 60, 90, 120, and 150 ft seaward of the shoreline. For site 1, the fairly large 30-ft data sample spacing was selected because values of seafloor slope were quite small and uniform (never larger than about 3 percent within a given 30-ft distance of STV test path). Also, the beach slope at site 1 was moderate enough to allow the STV test support equipment to be positioned such that the STV traveled well over 200 ft out into the ocean in all but one test.

44. At site 2, the seafloor slope was significantly larger than at site 1 (about 7 percent at site 2, based on differences in elevations at the shoreline and at 150 ft seaward) with a rather severe seafloor shelf about 10 to 15 ft wide and over 20 percent slope located roughly parallel to the shoreline and about 30 to 40 ft offshore. A data sample spacing of 10 ft was used for STV travel up to 40 ft into the ocean at site 2 to reflect test results that might be influenced by the fairly large local seafloor slopes near the shoreline. Beyond about 40 ft, the seafloor slope was moderate and the test data sample spacing was increased. Also, the slope of the beach near the shoreline was much larger at site 2 than at site 1, so that an area suitably level for locating the STV test support equipment was located about 150 ft landward of the shoreline (versus about 100 ft landward at site 1). With the support equipment in this location, the STV could travel only slightly over 150 ft into the ocean before the bundled instrumentation and hydraulic lines reached full payout.

Evaluation of STV test results relative to STAM predictions

45. As seen in Table 3, each 20 percent slip test began with the STV at the shoreline and progressed until the STV was either submerged or nearly submerged at the end of the test. (For the 12,250-, 17,650-, and 22,650-lb gross vehicle weights, the STV became completely submerged

* The only exception was Test No. 20, which ended with the STV approximately 200 ft from the shoreline.

at water depths of 46, 52.5, and 59 in., respectively.) In the constant slip tests, then, the appropriate measure of STV weight was vehicle effective weight VEW defined as vehicle total weight, including payload, with buoyancy taken into account (as shown in Figure 2).

46. For the STV operating in water deep enough that buoyancy must be taken into account (as was the case in all the constant 20 percent slip tests), the sand-track mobility number N_s' is defined as

$$N_s' = \frac{CI_{0-6}\ (TW \times TLC)^{1.5}}{1.75\ VEW} \qquad (6)$$

(For the previously described STV variable slip tests in submerged sand, water depth was never greater than a few inches so that N_s defined by Equation 3 was adequate for those tests.) The more general expression for N_s' applicable to any given tracked vehicle at any level of vehicle submergence is

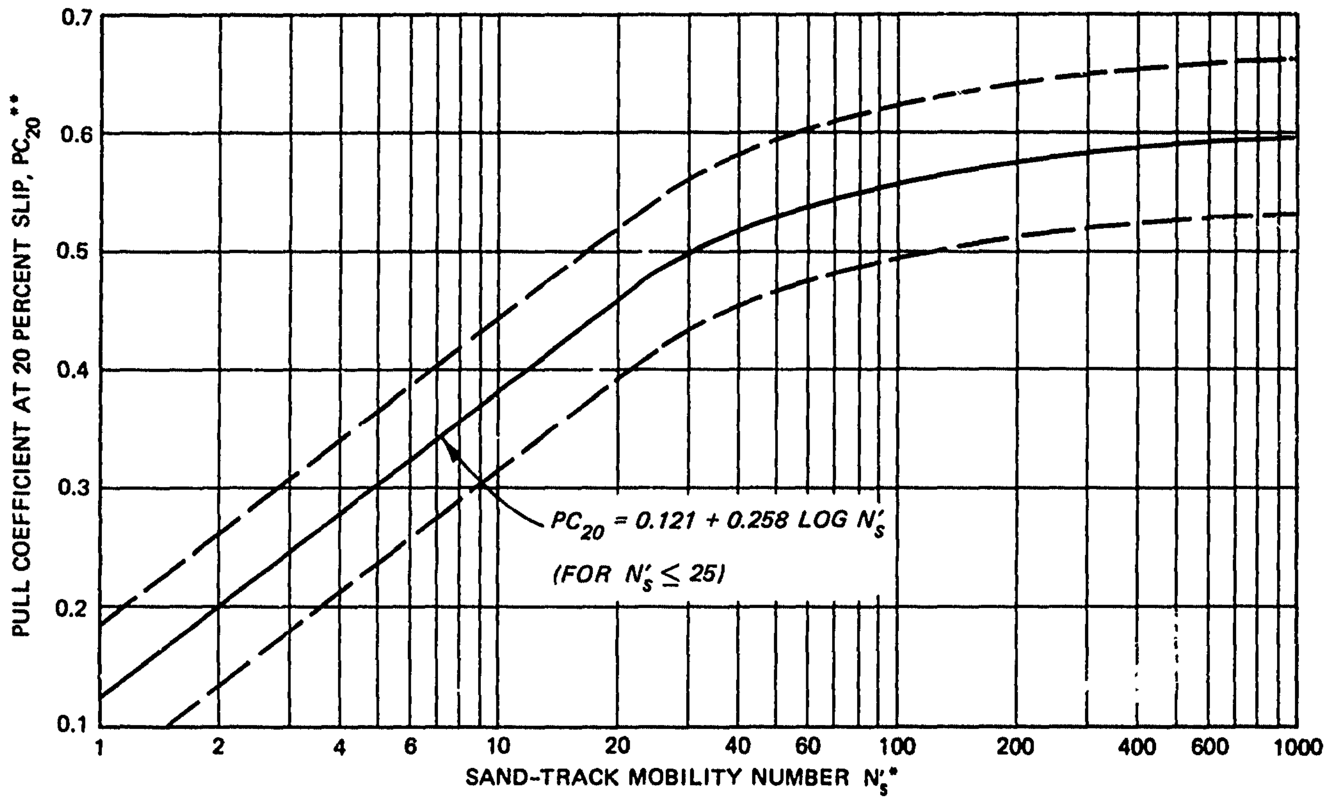
$$N_s' = \frac{G(TW \times TLC)^{1.5}}{0.5\ VEW} \cdot \left(\frac{VEW}{VEW_t}\right)^{0.5} \cdot \left(\frac{d}{TLC/2}\right)^{n} \qquad (7)$$

47. For a tracked vehicle operating on a downslope of angle θ deg , the appropriate dimensionless term to describe drawbar pull performance at 20 percent slip is $(DBP_{20} - VEW \sin\theta)/VEW$, or $\frac{DBP_{20}}{VEW} - \sin\theta$. This term arises because $VEW \sin\theta$ acts in the same direction as DBP_{20} and adds to the measured value of DBP_{20} for a vehicle moving downslope. Since the intent of the dimensionless term is to describe tracked vehicle drawbar pull performance free of the influence of seafloor slope, $VEW \sin\theta$ must be subtracted from measured DBP_{20} . In similar fashion, the appropriate dimensionless term to describe the drawbar pull performance of a tracked vehicle operating on a seafloor upslope of θ deg is $\frac{DBP_{20}}{VEW} + \sin\theta$, and for such a vehicle operating on a level seafloor, $\frac{DBP_{20}}{VEW}$. Hereafter, the term PC_{20} will be used to designate drawbar pull coefficient at 20 percent slip with each of the three possible slope conditions taken into account.

48. In accord with the considerations of vehicle buoyancy and seafloor slope in paragraphs 46 and 47, respectively, the description of in-sand tracked vehicle drawbar pull performance at 20 percent slip in Figure 12 was modified to the relation shown in Figure 14. The PC_{20} versus N'_s relation in Figure 14 is simply a more general version of the Figure 12 relation and applies to a broad range of combinations of rigid- and flexible-suspension tracked vehicles, sand strengths and wetness conditions (dry to submerged), seafloor slopes, and water depths (from zero to full vehicle submergence). 41

49. For the constant slip STV tests, the appropriate ordinate term in the Figure 14 relation is $\frac{DBP_{20}}{VEW} - \sin\theta$ (since each test was conducted downslope as the STV moved oceanward from the shoreline), and the appropriate abscissa term is N'_s as defined by Equation 6. It was expected that the STV constant slip test data would define a $\frac{DBP_{20}}{VEW} - \sin\theta$ versus N'_s relation qualitatively like that in Figure 14--i.e., $\frac{DBP_{20}}{VEW} - \sin\theta$ was anticipated to increase in a well-defined semilogarithmic pattern as a function of N'_s. For Test No. 12 through 20, the constant slip STV tests conducted at site 1, Figure 15a shows that this general result was obtained. In particular, however, the ordinate values of the data in Figure 15a are similar to those defined by the dash lines in Figure 14 only at the smallest abscissa value of the data in Figure 15a, which was about 195. As values of the abscissa terms in Figure 14 and 15a increase well beyond 195, the test data in Figure 15a define ordiante term values that become increasingly larger than the corresponding ordinate values in Figure 14.

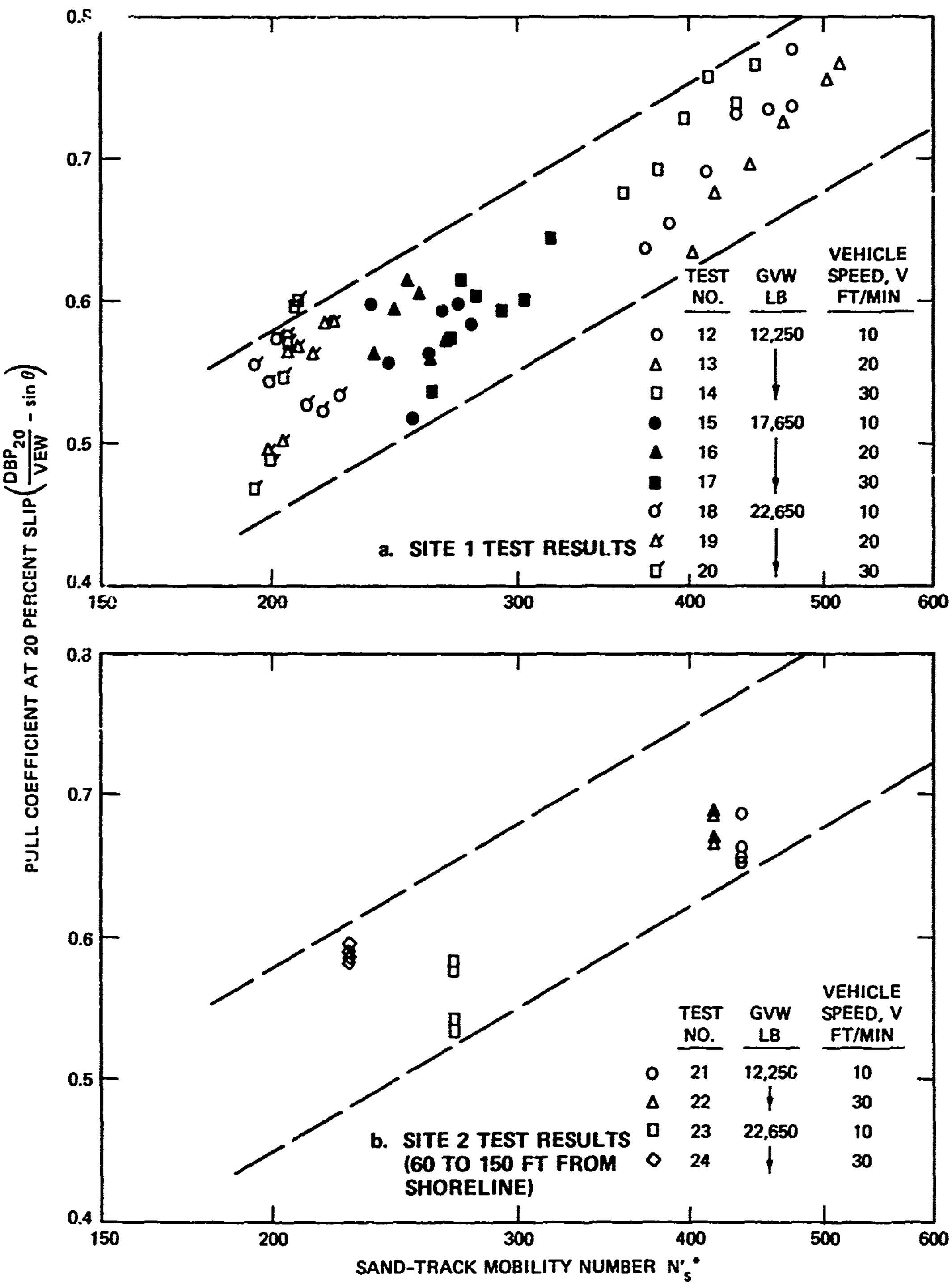
50. Figure 15b illustrates the relation between $\frac{DBP_{20}}{VEW} - \sin\theta$ and N'_s based on the site 2 STV constant slip test results obtained only at distances 60 to 150 ft from the shoreline. Individual data points taken within the first 40 ft from shoreline in the constant slip STV tests at site 2 are not plotted in Figure 15b because of the somewhat suspect nature of DBP_{20} values measured within this distance and the



$$^{*}N'_s = \frac{G(TW \times TLC)^{1.5}}{0.5\ VEW} \cdot \left(\frac{VEW}{VEW_t}\right)^{0.5} \cdot \left(\frac{d}{TLC/2}\right)^n$$

$$^{**}PC_{20} = \frac{DBP_{20}}{VEW}, \frac{DBP_{20}}{VEW} - \sin\theta, \text{ OR } \frac{DBP_{20}}{VEW} + \sin\theta$$ FOR A TRACKED VEHICLE OPERATING ON LEVEL GROUND, ON A DOWNSLOPE OF θ DEG, OR ON AN UPSLOPE OF θ DEG, RESPECTIVELY

Figure 14. General relation of pull coefficient at 20 percent slip to sand-track mobility number N'_s



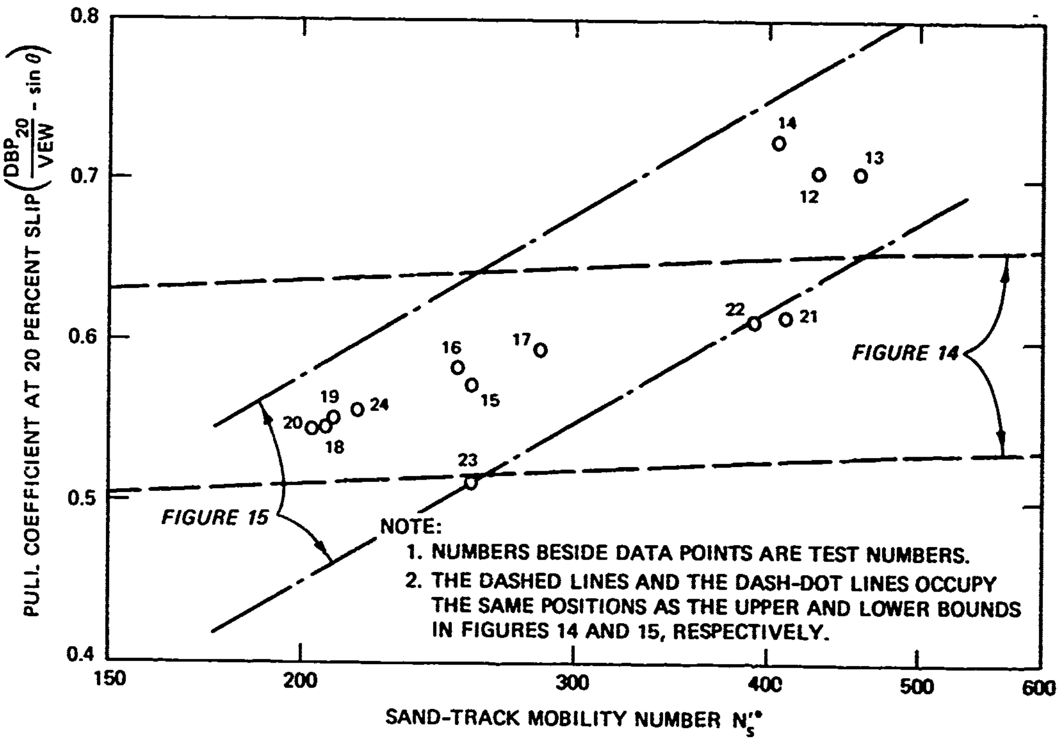
$$*N'_s = \frac{CI_{0-6}(TW \times TLC)^{1.5}}{1.75\ VEW}$$

Figure 15. Relation of pull coefficient at 20 percent slip to sand-track mobility number N'_s based on STV constant slip test results expressed as individual data points

resulting influence of these values on values of $\frac{DBP_{20}}{VEW} - \sin\theta$ computed during data analysis. For each site 2 STV constant slip test, measured values of DBP_{20} changed only moderately as the test progressed from shoreline to 150 ft oceanward (see column 17 in Table 3 for Test No. 21 through 24). This resulted primarily because the winch system used to provide drawbar reaction force was somewhat insensitive. Thus, the winch operator was unable to react quickly to changing seafloor slope values while applying a variable reaction force intended to maintain STV slip nearly constant at 20 percent. This insensitivity in the production of measured DBP_{20} values led to values of $\frac{DBP_{20}}{VEW} - \sin\theta$ within the first 40 ft from shoreline being noticeably different from (generally smaller than) values of $\frac{DBP_{20}}{VEW} - \sin\theta$ at distances 60 to 150 ft from shoreline, mainly because the substantially larger values of seafloor local slope θ within the first 40 ft from shoreline significantly influenced the values of $\frac{DBP_{20}}{VEW} - \sin\theta$. Thus, it is considered reasonable in Figure 15b in dealing with individual test data points to consider data only at distances 60 to 150 ft from the shoreline, where slopes were sufficiently small to cause winch insensitivity to negligibly affect measured STV DBP_{20} performance. These data lie within the scatter band of the $\frac{DBP_{20}}{VEW} - \sin\theta$ versus N_s' relation in Figure 15a, reinforcing the pattern of STV drawbar pull performance defined by the Figure 15a relation. In both Figures 15a and 15b, there is no consistent separation of the test data by vehicle speed, indicating that STV $\frac{DBP_{20}}{VEW} - \sin\theta$ performance was negligibly influenced by vehicle speeds of 10, 20, and 30 ft/min.

51. In summarizing the results of the constant slip STV tests on the basis of average test values, Figure 16 shows the relation of $\frac{DBP_{20}}{VEW} - \sin\theta$ to N_s' with each data point representing the average value of a given test based on data sampled at distances from 0 to 150 ft from shoreline. (Numbers beside data points in Figure 16 are test numbers.) The dashed lines in Figure 16 occupy the same positions as the upper and lower bounds of the general PC_{20} versus N_s' relation in Figure 14,

and the dash-dot lines occupy the same positions as the upper and lower bounds of the $\frac{DBP_{20}}{VEW} - \sin\theta$ versus N'_s relation in Figure 15. While only 3 of the 13 data points in Figure 16 lie outside of the dashed lines, the overall data trend is for $\frac{DBP_{20}}{VEW} - \sin\theta$ to increase at a faster rate than indicated by the dashed lines, at least for N'_s values larger than about 400. Based on the data in Figure 16, the relation indicated by the dashed lines is somewhat conservative--i.e., it either closely predicts or slightly underpredicts $\frac{DBP_{20}}{VEW} - \sin\theta$, depending on whether N'_s is less than or greater than about 400.



$$*N'_s = \frac{CI_{0-6}(TW \times TLC)^{1.5}}{1.75\ VEW}$$

Figure 16. Relation of pull coefficient at 20 percent slip to sand-track mobility number N'_s based on average values from STV constant slip tests

52. It is concluded that the relation described by the central curve in Figure 14 is reasonable (though somewhat conservative for large N'_s values) to describe the 20 percent slip drawbar pull performance of tracked vehicles in coarse-grained soil nearshore regions. How this conclusion should be incorporated into STAM is described in the next few paragraphs.

Modifications to STAM

53. For tracked vehicles with rigid suspensions (like the STV) operating on level ground in coarse-grained soils, the STAM* predicts that the pull coefficient at 20 percent slip is defined by

$$PC_{20} = 0.56 \quad (8)$$

54. It is useful to consider the simplified description of in-sand tracked vehicle pull performance provided by Equation 8 relative to the general description of such performance in Figure 14 and to the results of the STV constant 20 percent slip tests. In Figure 14, the 0.56 value specified by Equation 8 occurs at a central curve value of approximately $N'_s = 100$. Thus, for N'_s values of about 100 and larger, the 0.56 value in Equation 8 is somewhat conservative compared to the Figure 14 pull coefficient values. The equation $PC_{20} = 0.56$ is more conservative still when compared to values of $\frac{DBP}{VEW} - \sin\theta$ obtained in the STV tests at N'_s values of about 400 and larger.

55. The relation in Equation 8 is based on field test results of several full-size tracked vehicles operating in a variety of coarse-grained soils at N'_s values well over 100.** On the other hand, the model track test data in Figure 12 (which were used to define the relation in Figure 14) and the STV test data reported herein, taken together, reflect only a relatively small body of experience. Thus, it

---

* Turnage and Seabergh, op. cit., p 5.

** A. A. Rula and C. J. Nuttall, Jr. 1971. "An Analysis of Ground Mobility Models (ANAMOB)," Technical Report M-71-4, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

is considered prudent to continue using conservative Equation 8 in STAM to describe rigid-suspension tracked vehicle pull performance in coarse-grained soil nearshore areas. The necessary modification to STAM relative to Equation 8 is that this equation be applied only for sand-track situations described by N'_s values of 100 and larger. For ordinary rigid-suspension tracked vehicles and even very low sand strengths, N'_s nearly always will take a value larger than 100. For those unusual cases where N'_s is less than 100, rigid-suspension tracked vehicle performance should be described according to the relation in Figure 14 for $N'_s < 100$.

56. Unfortunately, the STV tests were not designed to validate the relation

$$\frac{TMR}{VEW} = 0.074 \tag{9}$$

which STAM used to predict the total motion resistance TMR developed by a rigid-suspension tracked vehicle operating in a coarse-grained soil nearshore region. TMR is defined as the sum of external motion resistance (the resistance to movement of a vehicle provided by the surface on and through which the vehicle moves) and internal motion resistance (the resistance to vehicle movement provided by the internal friction of the vehicle's moving parts and the energy losses in its traction elements). Also, because the STV has a rigid suspension, it was not possible to validate the STAM relations for predicting DBP_{20} and TMR for a tracked vehicle with <u>flexible</u> suspension in a coarse-grained soil nearshore region, described as follows:

$$PC_{20} = 0.50 \tag{10}$$

and

$$\frac{TMR}{VEW} = 0.100 \tag{11}$$

57. Like Equation 8, however, Equations 9 through 11 describe relations based on field test results of several full-size tracked

vehicles operating in a variety of coarse-grained soils.* Lacking STV field validation test results relative to Equations 9 through 11, it is reasonable to draw inferences from (a) the relations expressed by Equations 9 through 11, (b) the basic finding of the analysis in paragraphs 45 to 55 (i.e., that the STV field validation tests indicate that the description of rigid-suspension tracked vehicle performance in a coarse-grained soil nearshore region provided by STAM is adequate and slightly conservative), and (c) results of model track tests in dry sand.* On this basis, Equations 9 and 11 can be used for tracked vehicles operating in coarse-grained soil nearshore regions without concern for the value of N'_s. This situation arises from the fact that the relation of TMR/GVW to N_s for model track tests in dry sand is essentially constant for N_s values larger than about 20.** It is reasonable to anticipate that the corresponding relations of TMR/VEW to N'_s for rigid- and flexible-suspension tracked vehicles described by Equations 9 and 11, respectively, are also applicable for N'_s values down to about 20, an N'_s situation that nearly always will prevail in the nearshore region.

58. As was the case for Equation 8, Equation 10 can be used for $N'_s \geq 100$, a condition that will usually be satisfied by flexible-suspension tracked vehicles operating in nearshore coarse-grained soil environments. Since Equation 10 for flexible-suspension tracked vehicles produces estimates of drawbar pull coefficient 0.06 smaller than those produced by corresponding Equation 8 for rigid-suspension tracked vehicles, the curve describing the relation in Figure 14 for $N'_s < 100$ should be modified for flexible-suspension tracked vehicles by decreasing the curve's ordinate values by 0.06.

59. The computer program of STAM has now been modified to reflect the relations described in paragraphs 53 to 58.

---

* Rula and Nuttall, op. cit., p 48.

** Turnage, op. cit., p 33.

Suggested Additional Validation Testing of STAM

An overview of the
present status of STAM

60. Prior to the study described herein, STAM described bottom-crawling tracked vehicle performance in the nearshore region on the basis of a detailed, quantitative, desk-study analysis of two aspects of vehicle performance--vehicle stability and vehicle trafficability.

61. Vehicle stability is described in STAM in terms of the vehicle's ability to maintain forward (or rearward) motion and to resist side sliding while working on the seafloor. The STV field test program reported herein was not designed to evaluate STV stability performance. It is worth mentioning, however, that no problems were encountered in terms of the STV's ability to maintain near-constant speed in the 20 percent slip tests at either site 1 or site 2 during STV movement into the ocean. Current velocities at the two sites were fairly sizeable (up to about 5 ft/sec at site 2); wave forces at the two sites were sometimes large and easily distinguishable on the STV drawbar pull record (as produced by waves of up to about 4 ft in height); and the STV had to negotiate a steep local slope (greater than 20 percent over a distance of about 10 to 15 ft at site 2). Testing is needed to validate quantitatively and in detail the description of vehicle stability performance presently included in STAM (more on this later); the STV tests showed that for the moderately difficult current/wave force/seafloor slope conditions encountered, bottom-crawler stability was not a significant problem.*

62. In STAM the major functions of the trafficability submodel are to predict in quantitative terms the ability of a bottom-crawling tracked vehicle to (a) negotiate soft soil, (b) develop drawbar pull,

---

* The seafloor conditions encountered by the STV did not include any significant side slopes. The seafloor shelf at site 2 was traversed essentially head-on in each constant slip test so that differences in the side-to-side elevations of the STV at any given point along the STV's length were always small.

(c) climb a slope, and (d) override an obstacle. In connection with obstacle override, the trafficability submodel of STAM checks to determine whether or not vehicle hangup occurs because of the relative geometries of the vehicle and the obstacle. The only notable geometric obstacle encountered during the STV tests was the seafloor shelf described earlier, and it presented little difficulty to STV movement.

63. The other major check made by the trafficability submodel is to determine whether tractive force available from vehicle/soil interaction is sufficient to satisfy pull and tractive force requirements of items (a) through (d) in paragraph 62. The applicable equations are:

$$\text{Available DBP} = \text{DBP} \cos \theta \tag{12}$$

$$\text{Available TF} = (\text{DBP} + \text{TMR}) \cos \theta \tag{13}$$

$$\text{Required } \text{TF}_1 = \text{TMR} + \text{VEW} \sin \theta + \text{Required DBP} \tag{14}$$

$$\text{Required } \text{TF}_2 = \text{Required } \text{TF}_1 + \text{Required } \text{TF}_0 \tag{15}$$

where

θ = seafloor local slope, deg

TF = tractive force, lb

TF_0 = tractive force required for obstacle override, lb

64. In applying Equations 12 through 15, values of θ, required DBP, and VEW should be known beforehand for a given tracked vehicle/nearshore environment scenario. Then, predictions of available DBP and TF and of required TF_1 and TF_2 can be made by predicting DBP, TMR, and required TF_0. Paragraphs 53 through 58 herein describe the updated relations that STAM now uses to predict DBP and TMR for tracked vehicles operating in coarse-grained soil nearshore regions. A previous report* presents relations entirely different from those in paragraphs 53 to 58 that STAM uses to predict DBP and TMR for tracked vehicles in fine-grained soil nearshore environments, and it also cites the relations that the computerized STAM uses to predict required TF_0.

---

* Turnage and Seabergh, op. cit., p 5.

Suggested further STAM validation testing

65. Because STAM quantitatively predicts tracked vehicle performance in the nearshore environment, which by today's standards is fairly remote to bottom-crawling work vehicles, it is important before using STAM in real-world situations to validate as many of the major STAM vehicle performance prediction relations as possible. Relations yet to be validated include all of those in STAM's water force calculations and vehicle stability submodels, plus all of those in STAM's trafficability submodel, except for the relations described in paragraphs 53 to 58 herein. (The STV tests did not generate data for validating the relations described by Equations 9 through 11 per se. However, the inferences drawn in paragraphs 56 to 58 relative to these equations, together with the restrictions described for the use of these equations in terms of N'_s values, are considered sufficient basis to allow Equations 9 through 11 to be used conservatively in STAM.)

66. In making suggestions to accomplish the still-needed STAM validation testing, it is useful to do so relative to recommendations b to e that were made by Turnage and Seabergh in the report that preceded this study.* Four of the recommendations (b to e) are first quoted and are then followed by pertinent comments relative to each recommendation. Summary comments are then made relative to results obtained in this study and to suggested further STAM validation testing taken as a whole.

---

* The first recommendation was that:

> "a. Study be undertaken to quantify turbidity and to develop a means for predicting its value as a function of pertinent nearshore environmental, vehicle design, and vehicle operational parameters."

A description of turbidity was not undertaken in the earlier report or herein. To have reasonably precise control either in guiding a nearshore bottom crawler or in monitoring its performance by underwater visual means (by man-in-the-sea or by television) requires that the objectives of recommendation a be accomplished. Initial testing to satisfy these objectives should begin with carefully controlled laboratory testing and progress according to the stages described in the last sentence of e in paragraph 67.

67. The four recommendations are that:

"b. Research be conducted to develop a proven methodology for predicting vehicle trafficability performance in submerged coarse-grained (sandy) soils. Further, the methodology now incorporated in STAM for this purpose should, at a minimum, be refined in the next-generation version of STAM to reflect performance predicted as a function of the sand-track mobility number.

c. Work be done to incorporate into STAM the capability to predict accurately the influence of pitch and yaw (steering) articulation on the trafficability and stabiltiy performance of multiunit tracked vehicles.

d. In light of the difficulties in defining drag, inertial, and lift coefficients for a variety of underwater vehicles in an oscillatory velocity field, carefully conceived scale-model tests be conducted to evaluate these important coefficients. Further, scale-model testing of breaking wave forces should be done to gain insight into vehicle overturning problems and other potential vehicle operational constraints in high force regions where analytical solutions are not obtainable.

e. The first-generation, desk-study version of STAM developed in this report be refined and verified to predict actual nearshore vehicle trafficability and stability performance accurately. This should be accomplished in stages--first by scale-model laboratory testing; next by carefully controlled prototype vehicle testing in a precisely described nearshore region; and finally by practical applications involving a broad range of bottom-crawling vehicles and nearshore environments."

68. Comments pertinent to the above recommendations are as follows:

b. This study makes a strong start toward satisfying the objectives in recommendation b. The most notable prediction relations yet to be validated in the coarse-grained soil part of the STAM trafficability submodel are those that deal with predicting tracked vehicle ability to override obstacles.

c. There still does not exist an adequate mathematical model of the influence of pitch and yaw articulation on the in-soil performance of multiunit tracked vehicles. Because articulated vehicles have major performance advantages over conventional one-unit vehicles (particularly in terms of obstacle negotiation), a major effort should be made to develop a mathematical model that accurately describes articulated vehicle trafficability and stability performance. The model should be developed on a desk-study basis, but should agree with the limited

published results on articulated vehicle testing. Likely, additional validation test data will be needed, which can be obtained under the best control and probably at the least cost in scale-model testing conducted under laboratory conditions, possibly followed by carefully controlled field testing of a prototype vehicle.

d. To accurately predict the stability performance of a nearshore bottom-crawling vehicle, the STAM stability submodel must (1) receive from the water force calcula tions submodel an accurate input description of the water forces that act on the vehicle and (2) have equations of equilibrium and of motion that accurately define the interaction of the vehicle, the water forces, and seafloor obstacles. While the description of water forces on bottom-crawling vehicles in the present version of STAM is believed to be reasonable, it reflects interpretation and extrapolation of relations from a literature that provides very little information on vehicle/water force interactions per se. Also, the STAM equations of equilibrium and of motion for vehicles operating on the seafloor remain to be validated by physical testing. Not only should the scale-model testing of recommendation d in paragraph 67 be conducted relative to relations in STAM's water force calculations submodel, but also the range of conditions tested should be extended to permit validation of all major relations in the STAM stability submodel.

e. The three stages of testing recommended in the last sentence of e in paragraph 67 were intended to point the way toward the most orderly and least expensive refine ment and verification of STAM. With the STV now existent and in large measure field-proven, slight modifications to the e recommendation are in order. Relative to all major relations in the water force calculations submodel and in the vehicle stability submodel of STAM, it is still recommended that verification be undertaken in the same three stages described in e of paragraph 67. The same holds true for verifying those relations in STAM's trafficability submodel that describe vehicle/obstacle geometry hangup.

   Only for those relations in STAM's trafficability submodel that deal with the balance between available tractive force and required pull and tractive force should consideration be given to starting the validation process with the controlled prototype vehicle testing (or STV) stage (i.e., to skipping the scale-model testing stage). Even for these relations, skipping the scale-model testing stage likely will result in a penalty in

the quality of validation obtained, in addition to possible penalties in the long run in terms of increased validation time and cost. Equations 12 to 15 are the key ones to be validated in such STV testing, along with the equations* that predict DBP and TMR for bottom-crawling tracked vehicles operating in a fine-grained soil nearshore region.

69. To summarize, for a given tracked vehicle operating in a coarse-grained soil nearshore region, this study (a) validated a method for predicting the drawbar pull of a rigid-suspension tracked vehicle (see paragraphs 53 to 55) and (b) developed a reasonable basis for modifying relations in STAM to predict conservatively the total motion resistance of rigid-suspension tracked vehicles, and both drawbar pull and total motion resistance of flexible-suspension tracked vehicles (see paragraphs 56 to 58). STAM is now programmed to reflect the improved relations described in paragraphs 53 to 58. The suggestions for needed additional STAM validation testing presented in paragraphs 67 and 68 are intended to point the way to an orderly, thorough validation of all the key relations in STAM.

---

* Turnage and Seabergh, op. cit., p 5.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

70. The foregoing analysis is considered an adequate basis for the following conclusions:

- a. The prototype tracked Surfzone Test Vehicle (STV), a specially fabricated test vehicle designed to be controlled and its performance monitored by remote means in tests in the nearshore region, has unique physical characteristics that are described in detail in this report. The STV performed without fault mechanically in the beach/nearshore tests reported herein and produced results useful for validating and/or modifying several key prediction equations in STAM's trafficability submodel.
- b. For the variable slip STV tests, a single curve adequately described the relation of pull coefficient versus slip. This reflected the fact that the range of low to medium sand strengths in the STV test paths (average 0- to 6-in. cone index values from 38 to 96), in combination with the STV track size (24-in. width, 123-in. ground contact length) and test weights (gross vehicle weights (GVW's) of 12,250 and 22,650 lb), permitted the STV to attain near-maximum drawbar pull (DBP) performance that was negligibly influenced either by the three sand wetness conditions tested (dry, moist, and submerged) or by the narrow range of STV track test speeds (12.5 to 37.5 ft/min).
- c. On the basis of (1) the shape of the pull coefficient versus slip curve for the variable slip STV tests and (2) the relation of pull coefficient to tractive efficiency for a broad range of tracked vehicle/sand strength combinations, it was concluded that 20 percent was a reasonable nominal slip value to use in the subsequent STV constant slip tests to approximate tracked vehicle near-maximum DBP performance in the nearshore region.
- d. Based on results obtained in constant 20 percent slip STV tests at three gross vehicle weights (12,250, 17,650, and 22,650 lb) and three vehicle speeds (10, 20, and 30 ft/min) from the shoreline into the Pacific Ocean (to distances of 200 ft and more at one test site, 150 ft and more at a second site), the STV pull coefficient $(DBP_{20}/VEW) - \sin\theta$ (where VEW is vehicle effective weight and θ is local seafloor slope, in degrees) increased noticeably as the dimensionless sand-track

mobility number N'_s increased. The curve that describes the relation between pull coefficient and sand-track mobility number based on prior model track testing in dry sand was slightly conservative in estimating $(DBP_{20}/VEW) - \sin\theta$ results from the STV constant slip tests.

e. It was judged prudent to continue using the simple, slightly conservative equations for DBP_{20} and TMR (total motion resistance) already included in STAM for nearly all sand/tracked vehicle/vehicle submergence situations in the beach/nearshore region. For tracked vehicles with rigid suspensions, these relations are $PC_{20} = 0.56$ (where PC_{20} = pull coefficient at 20 percent slip, defined as DBP_{20}/VEW, $(DBP_{20}/VEW) - \sin\theta$, or $(DBP_{20}/VEW) + \sin\theta$ for a tracked vehicle operating on level ground, on a downslope of θ deg, or on an upslope of θ deg, respectively) and $TMR/VEW = 0.074$; for tracked vehicles with flexible suspensions, $PC_{20} = 0.50$ and $TMR/VEW = 0.100$. For extreme conditions of low sand strength and high tracked vehicle ground contact pressure (quantified by N'_s values smaller than 100), STAM relations were modified to predict significantly smaller values of PC_{20} for both rigid- and flexible-suspension tracked vehicles. (Relations relative to equation $PC_{20} = 0.56$ were validated by the STV test data; those relative to equations $TMR/VEW = 0.074$, $PC_{20} = 0.50$, and $TMR/VEW = 0.100$ were inferred from results of both the STV tests and previous tracked vehicle and model track testing.)

Recommendations

71. It is recommended that:

a. Testing and analysis be done to complete the validation of all major performance prediction relations in STAM. Relations yet to be validated include all of those in STAM's water force calculations and vehicle stability submodels, plus a majority of those in STAM's trafficability submodel. (None of the trafficability submodel relations has been validated for tracked vehicles operating in fine-grained soil nearshore regions, nor have relations been validated for describing obstacle override or the balance between required and available tractive force for tracked vehicles in coarse-grained soil nearshore regions.)

b. The suggestions made in paragraphs 67 and 68 be taken into account in further STAM validation efforts. Generally, these efforts should progress from scale-model laboratory testing to carefully controlled prototype vehicle testing in a precisely described nearshore region to practical applications involving a broad range of bottom-crawling vehicles and nearshore environments, with account taken of the availabiltiy of the STV in further validation testing of STAM's trafficability submodel prediction relations.

Table 1

Values of STV Characteristics Used by the Three Submodels of STAM

Symbol	STV Physical Characteristic Value(s)*
	Water Force Calculations Submodel
VL	152 in.
VHF	3.83 ft; 4.38 ft; 4.92 ft
VWF	7.75 ft
DRYWT	12,250 lb; 17,650 lb; 22,650 lb
SUBWT	9,460 lb; 14,438 lb; 19,015 lb
	Trafficability Submodel
VT**	0
GVW	12,250 lb; 17,650 lb; 22,650 lb
VL	152 in.
VW	93 in.
HLE	35.5 in.
HAA	18.5 in.
GC	16 in.
DS	40 in.
DCG	69.5 in.; 70.2 in.; 71.1 in.
VAA	90 deg
ACG	1 deg; 6 deg; 10 deg
FLEW	24,500 lb; 35,300 lb; 45,300 lb
TLC	123 in.
TL	118 in.
TW	24 in.
ATS	384 in.^{2}
BN	12
GH	2.1 in.
TT†	1
TN	2
RWR	17.6 in.
RISR	17.6 in.
HRIS	15.6 in.
DRISCG	52.2 in.; 53.3 in.; 54.5 in.
XBC	0.8
CGF	65.6 in.
CGH	1.1 in.; 10.5 in.; 16.7 in.

(Continued)

* Each STV physical characteristic with a single value listed is unaffected by changes in vehicle payload; each one with three values listed is evaluated, in order, at payloads of 0, 5,400, and 10,400 lb for the in-air condition only.

** For vehicle type VT, 0 = tracked vehicle and 1 = wheeled vehicle.

† For track type TT, 0 = flexible and 1 = girderized.

(Sheet 1 of 3)

Table 1 (Continued)

Symbol	STV Physical Characteristic Value(s)
	Trafficability Submodel (Continued)
REC	35.5 in.
RWW	9 in.
VDA	90 deg
TVAR*	0
EFF	0.95
FDR	1
FDREF	0.95
HPT	13.4 hp/ton; 9.3 hp/ton; 7.2 hp/ton

Symbol	DSS ft/min	DSS mph	TF, lb
Coordinates of drive sprocket speed (DSS) versus tractive force (TF) curve	1	0.0114	25,979
	5	0.0568	25,958
	10	0.1136	25,893
	15	0.1704	25,785
	20	0.2272	25,634
	25	0.2840	25,439
	30	0.3408	25,201
	35	0.3976	24,919
	40	0.4544	24,594
	45	0.5112	24,226
	50	0.5680	23,815
	55	0.6248	23,360
	60	0.6816	22,862

Symbol	STV Physical Characteristic Value(s)
	Stability Submodel
j	18.8 in.; 28.1 in.; 34.3 in.
b	69 in.
ℓ_1, ℓ_2	69 in., 83 in.
J_o	80,600 lb-in.-sec^2; 131,100 lb-in.-sec^2; 186,800 lb-in.-sec^2
J_p**	94,600 lb-in.-sec^2; 166,300 lb-in.-sec^2; 232,800 lb-in.-sec^2
	160,000 lb-in.-sec^2; 255,000 lb-in.-sec^2; 351,600 lb-in.-sec^2

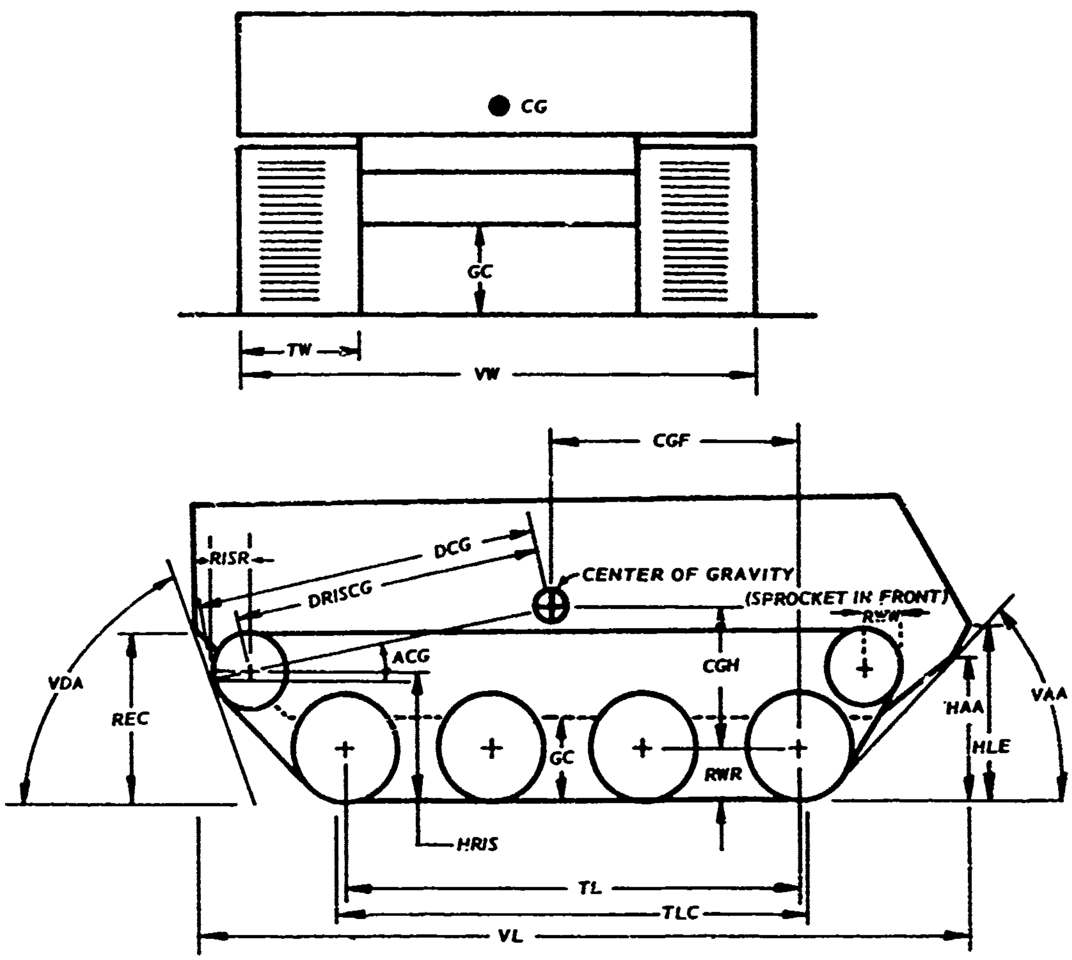
(Continued)

* For TVAR, 0 = automatic and 1 = manual transmission.

** The first set of J_p values is for P located at the bottom, rearmost point of the vehicle's tracks; the second set is for P at the bottom, frontmost point of the vehicle's tracks.

(Sheet 2 of 3)

Table 1 (Concluded)



Tracked vehicle description in terms of STAM trafficability submodel vehicle geometric characteristics

(Sheet 3 of 3)

Table 2

Variable Slip STAM Validation Tests with the Surfzone Test Vehicle

(1) Test No.	(2) Test Location	(3) Sand Condition	(4) STV Payload lb	(5) STV Gross Vehicle Weight (GVW), lb	(6) STV Track Speed (T) Nominal ft/min	(7) STV Track Speed (T) Actual ft/min	(8) STV Pitch Angle* deg	(9) Hydraulic Horsepower Input (HYDHP) hp	(10) Cone Index (CI_{0-6})	(11) STV Vehicle Speed (V) ft/min	(12) STV Slip (S) percent	(13) STV Drawbar Pull (DBP) lb	(14) STV P[illegible]** Coeff[illegible]cient ([illegible]/GVW)
1	Site 1, landward of berm crest	Dry	10,400	22,650	12.5	13.0	-2.0	5.1	48, 46 (47)	12.2	6.2	8,201	[illegible].362
						15.0	-3.2	7.1		14.3	4.7	9,640	0.426
						15.2	-2.3	9.5		13.9	13.1	13,971	0.617
						15.9	-1.9	8.6		12.8	19.5	13,919	0.615
						13.7	-1.7	7.9		11.8	13.9	13,87[illegible]	0.613
						14.4	-1.4	9.2		13.0	16.7	14,[illegible]	0.642
						16.1	-1.4	11.3		10.0	37.9	15,[illegible]	0.665
						12.2	-1.8	8.4		5.0	59.0	[illegible]57	0.674
2	Site 1, landward of berm crest	Dry	10,400	22,650	25.0	24.0	-2.9	11.7	57, 50 (54)	22.2	7.5	[illegible],594	0.291
						25.5	-2.8	13.8		23.1	9.4	9,755	0.431
						27.5	-2.7	18.0		25.0	9.1	9,893	0.437
						26.5	-2.4	16.2		25.0	5.7	9,218	0.407
						24.9	-2.3	16.7		24.0	3.6	8,552	0.378
						24.7	-2.6	22.4		22.2	10.[illegible]	10,195	0.450
						25.2	-2.8	21.8		21.4	15.[illegible]	13,432	0.593
						26.0	-2.9	23.9		20.0	2[illegible]	14,683	0.648
						23.4	-2.5	22.2		6.2	73.5	15,191	0.671
3	Site 1, landward of berm crest	Dry	10,400	22,650	37.5	33.2	-1.2	25.4	61, 49 (55)	31.6	4.8	6,324	0.279
						34.8	-1.9	30.5		33.3	4.3	7,235	0.319
						35.1	-1.9	34.1		31.6	10.0	9,602	0.424
						36.8	-2.1	35.6		33.3	9.5	10,584	0.467
						35.9	-1.9	34.5		33.3	7.2	9,842	0.435
						36.5	-2.3	32.6		32.4	11.2	10,184	0.450
						35.9	-1.6	38.1		27.9	22.3	13,090	0.578
						35.3	-1.4	14.7		30.0	15.0	14,183	0.626
4	Site 1, seaward of berm crest	Moist	0	12,250	12.5	16.4	0.8	3.1	46, 64 (55)	15.6	4.9	4,101	0.335
						16.9	0.8	3.0		15.8	6.5	3,640	0.297
						16.5	0.3	2.5		15.4	6.7	3,603	0.294
						16.1	-0.4	2.6		15.0	6.8	3,800	0.310
						15.9	-0.3	2.9		14.8	6.9	4,273	0.349
						16.3	-0.1	3.6		14.9	8.6	5,353	0.437
						16.5	0.0	4.3		14.6	11.5	6,807	0.556
5	Site 1, seaward of berm crest	Moist	0	12,250	37.5	36.7	-2.2	17.9	85, 107 (96)	34.3	6.5	3,677	0.300
						36.1	-2.2	20.4		33.0	8.6	4,890	0.399
						36.5	-2.0	22.2		32.6	10.7	6,352	0.519
						35.7	-2.1	22.1		31.6	11.5	6,931	0.566
						35.9	-2.0	22.7		30.8	14.2	7,667	0.626
						35.6	-1.9	22.6		28.6	19.7	7,850	0.641
6	Site 1, seaward of berm crest	Moist	10,400	22,650	12.5	12.9	-0.3	1.1	46, 56 (51)	12.3	4.7	1,686	0.074
						14.9	0.3	1.2		14.6	2.0	1,780	0.079
						15.1	0.7	3.7		14.3	5.3	5,950	0.263
						15.1	0.7	3.8		14.1	6.6	6,618	0.292
						14.6	0.8	3.6		13.9	4.8	6,211	0.274
						15.0	0.8	5.0		13.8	8.0	8,818	0.389
						15.2	0.8	6.6		14.0	7.9	9,426	0.416
						14.8	1.1	7.1		13.6	8.1	9,974	0.441
						14.6	1.2	6.9		13.0	11.0	11,695	0.516

* A positive pitch angle indicates that the longitudinal centerline of the STV was tilted downward at its front end, and a negative angle that it was tilted upward.

** Because site selection measurements in the site 1 test area showed very small values of beach and seafloor slopes (none larger than 3 percent), values of STV pull coefficient reported in this table are not corrected for slope.

(Continued)

Table 2 (Concluded)

(1) Test No.	(2) Test Location	(3) Sand Condition	(4) STV Payload lb	(5) STV Gross Vehicle Weight (GVW), lb	(6) STV Track Speed (T) Nominal ft/min	(7) STV Track Speed (T) Actual ft/min	(8) STV Pitch Angle deg	(9) Hydraulic Horsepower Input (HYDHP) hp	(10) Cone Index (CI_{0-6})	(11) STV Vehicle Speed (V) ft/min	(12) STV Slip (S) percent	(13) STV Drawbar Pull (DBP) lb	(14) STV Pull Coefficient (DBP/GVW)
7	Site 1, seaward of berm crest	Moist	10,400	22,650	37.5	31.9	-2.1	21.4	68, 87 (78)	30.0	6.0	3,826	0.169
						33.5	-2.6	20.4		31.6	5.7	3,900	0.172
						33.1	-2.4	21.0		31.9	3.6	5,424	0.239
						35.4	-2.3	28.6		32.7	7.6	9,113	0.402
						36.3	-2.4	27.1		33.8	6.9	9,508	0.420
						33.6	-2.2	25.6		31.6	6.0	9,534	0.421
						35.7	-2.0	29.2		30.0	11.0	11,587	0.512
						35.5	-1.9	34.0		28.6	19.4	13,764	0.608
						35.7	-2.0	34.7		29.1	18.5	14,548	0.642
8	Site 1, in water-covered sand	Submerged	0	12,250	12.5	15.1	-1.8	2.7	40, 36 (38)	14.0	7.3	4,432	0.362
						15.6	-1.0	2.8		14.6	6.4	4,802	0.392
						14.7	-1.8	3.0		13.6	7.5	4,834	0.395
						14.4	-0.9	3.9		12.2	15.3	7,547	0.616
						15.1	-0.4	4.2		10.7	29.1	7,965	0.650
9	Site 1, in water-covered sand	Submerged	0	12,250	37.5	38.3	-0.5	16.8	52, 47, 45 (48)	36.7	4.7	4,802	0.392
						38.1	-0.3	17.4		35.3	7.3	4,944	0.404
						38.1	-0.3	17.2		34.5	9.4	5,557	0.454
						37.9	-0.3	18.0		34.3	9.5	6,753	0.552
						36.6	-0.5	17.5		32.6	10.9	6,409	0.523
						38.4	0.0	19.7		33.4	13.0	6,609	0.540
						37.9	0.5	19.2		31.1	17.9	7,452	0.608
						38.2	0.2	20.0		28.4	23.0	8,051	0.657
10	Site 1, in water-covered sand	Submerged	10,400	22,650	12.5	17.3	-2.0	2.9	53, 49, 33 (45)	16.9	4.9	4,282	0.189
						16.7	-2.0	5.9		15.6	6.5	10,087	0.445
						15.6	-0.3	7.8		13.3	14.7	13,149	0.581
						17.3	-0.1	9.6		15.0	13.3	13,830	0.611
						21.4	-1.0	10.8		17.1	20.0	13,781	0.608
11	Site 1, in water-covered sand	Submerged	10,400	22,650	37.5	36.5	-2.2	20.4	48, 63, 43 (51)	34.4	5.8	5,959	0.263
						36.1	-2.3	22.4		34.8	3.6	8,536	0.377
						36.4	-2.2	36.8		34.0	4.4	8,555	0.378
						37.0	-2.4	29.6		31.8	14.1	14,174	0.626
						37.2	-2.4	33.4		32.0	11.6	12,827	0.566
						37.0	-2.3	38.1		33.3	10.0	12,660	0.559
						36.0	-2.3	36.1		30.0	16.7	12,599	0.556

(Sheet 2 of 2)

Table 3

Constant 20-Percent Slip STAM Validation Tests with the Surface Test Vehicle

(1) Test No.	(2) Location	(3) Approximate Current Velocity ft/sec	(4) Wave Height ft	(5) Wave Period sec	(6) STV Payload lb	(7) STV In-Air Gross Vehicle Weight (GVW) lb	(8) Nominal STV Vehicle Speed (V) ft/min	(9) STV Pitch Angle,* deg	(10) Hydraulic Horsepower Input (HYDHP) hp	(11) Cone Index (CI_{0-6})	(12) STV Slip (S_r), percent	(13) Approximate Distance from Shoreline ft	(14) Approximate Water Depth in.	(15) Approximate Local Slope percent	(16) STV Vehicle Effective Weight (VEW) lb	(17) Measured STV Drawbar Pull (DBP) lb	(18) DBP Corrected for Slope (DBP - VEW sin θ), lb	(19) STV Pull Coefficient ($\frac{DBP}{VEW}$ - sin θ)	(20) Sand-Track Mobility Number, N_s*+
12	Site 1, station 200, perpendicular to shoreline	2-4	3-4	12-15	0	12,250	10	--**	--	43, 41, 49, 70, 42 (49)	--	0	0		12,250	--	--	--	--
								-0.9	5.5		22.8	30	6	1.7	12,060	7,900	7,695	0.638	372
								1.8	5.4		19.9	60	13	1.9	11,6[illegible]	7,800	7,580	0.653	387
								2.3	4.8		19.9	90	24	3.1	10,890	7,850	7,512	0.690	412
								2.7	5.0		17.9	120	32	2.2	10,370	7,800	7,571	0.730	433
								2.3	5.0		20.5	150	40	2.2	9,850	7,450	7,233	0.734	456
								2.1	5.0		19.6	180	48	2.2	9,460	7,550	7,342	0.776	475
								2.3	5.2		18.2	210	55	1.9	9,460	7,150	6,970	0.737	475
13	Site 1, station 215, 20 deg from perpendicular to shoreline (away from pier)	2-4	3-4	12-15	0	12,250	20	--	--	52, 53, 54, 60, 47 (53)	--	0	0		12,250	--	--	--	--
								--	--		--	30	2	0.6	12,250	--	--	--	--
								1.8	13.6		13.4	60	5	0.8	12,125	7,750	7,653	0.631	401
								2.3	13.5		12.5	90	12	1.9	11,670	8,100	7,878	0.675	416
								2.7	13.8		11.9	120	22	2.8	11,020	7,950	7,641	0.693	441
								2.3	13.4		20.1	150	32	2.8	10,370	7,800	7,510	0.724	468
								3.2	12.6		20.0	180	43	3.1	9,655	7,550	7,251	0.751	503
								2.3	13.3		17.0	210	53	2.8	9,460	7,500	7,235	0.765	513
14	Site 1, station 185, 20 deg from perpendicular to shoreline (toward pier)	2-4	3-4	15-18	0	12,250	30	--	--	45, 59, 33, 51, 44 (46)	--	0	0		12,250	--	--	--	--
								--	--		--	30	4	1.1	12,190	--	--	--	--
								1.4	15.1		15.7	60	11	1.9	11,735	8,150	7,927	0.676	359
								2.3	16.1		17.6	90	21	2.8	11,085	7,975	7,665	0.691	380
								1.8	15.[illegible]		11.2	120	28	1.9	10,630	7,950	7,[illegible]48	0.729	397
								2.3	16		13.1	150	35	1.9	10,275	7,900	7,707	0.757	416
								2.1	16		19.2	150	42	1.9	9,720	7,300	7,165	0.737	434
								2.3	15.8		18.4	210	48	1.7	9,460	7,400	7,239	0.765	446
15	Site 1, station 265, 20 deg from perpendicular to shoreline (away from pier)	2-4	2-3	12-15	5,400	17,650	10	--	--	62, 28, 38, 53, 43 (45)	--	0	0		17,650	--	--	--	--
								-2.1	7.2		22.6	30	5	1.4	17,575	10,750	10,505	0.599	235
								-0.5	7.2		22.7	60	12	1.9	17,070	9,850	9,526	0.558	242
								1.4	6.9		19.6	90	23	3.1	16,355	9,000	8,493	0.519	252
								1.4	6.8		14.6	120	29	1.7	15,965	9,2[illegible]0	8,979	0.562	258
								2.3	6.3		[illegible]6	150	35	1.7	15,575	9,500	9,235	0.593	265
								2.7	7.1		[illegible]	180	41	1.7	15,185	9,350	9,092	0.599	272
								0.9	7.5		19.7	210	46	1.4	14,860	8,850	8,642	0.582	278
16	Site 1, station 250, perpendicular to shoreline	2-4	2-3	10-12	5,400	17,650	20	--	--	55, 44, 44, 48, 31 (44)	--	0	0		17,650	--	--	--	--
								--	--		--	30	5	1.4	17,525	--	--	--	--
								-2.7	15.8		20.1	60	12	1.9	17,070	9,9[illegible]0	9,576	0.561	235
								-1.4	15.2		26.1	90	21	2.5	16,485	10,175	9,763	0.592	245
								[illegible]	15.4		17.5	120	26	1.4	16,160	10,150	9,924	0.614	250
								-1.4	15.3		21.3	150	31	1.4	15,835	9,800	9,578	0.605	255
								0.0	16.2		18.4	180	36	1.4	15,510	8,925	8,708	0.561	260
								1.8	15.6		12.4	210	41	1.4	15,185	8,900	8,687	0.572	266

* A positive pitch angle indicates that the longitudinal centerline of the STV was tilted down at its front end, and a negative angle that it was tilted upward.

** For several of the STV 20 percent slip tests, values of the variables in columns 9, 10, 12 and 17 did not stabilize until the STV had traveled a short distance from the shoreline into the ocean. For these tests, dashes are shown in columns 9, 10, 12 and 17-19 for the STV near the shoreline.

+ For the STV operating in water deep enough that buoyancy must be taken into account, $N_s' = \frac{CI_{0-6}\,(TW \cdot TLC)^{1.5}}{1.75\,VEW}$.

(Continued)

(Sheet 1 of 3)

Table 3 (Continued)

(1) Test No.	(2) Location	(3) Approximate Current Velocity ft/sec	(4) Wave Height ft	(5) Wave Period sec	(6) STV Payload lb	(7) STV In-Air Gross Vehicle Weight (GVW) lb	(8) Nominal STV Vehicle Speed (V) ft/min	(9) STV Pitch Angle, deg	(10) Hydraulic Horsepower Input (HYDHP) hp	(11) Cone Index (CI_{0-6})	(12) STV Slip (S), percent	(13) Approximate Distance from Shoreline ft	(14) Approximate Water Depth in.	(15) Approximate Local Slope percent	(16) STV Vehicle Effective Weight (VEW) lb	(17) Measured STV Drawbar Pull (DBP) lb	(18) DBP Corrected for Slope (DBP − VEW sin θ), lb	(19) STV Pull Coefficient ($\frac{DBP}{VEW}$ − sin θ)	(20) Sand-Track Mobility Number, N_s
17	Site 1, station 235, 20 deg from perpendicular to shoreline (toward pier)	2-4	2-4	12-15	5,400	17,650	30	-1.6	24.9	60, 40, 70, 42, 37 (50)	12.0	0	0		17,650	9,950	--	--	--
								-1.8	24.3		12.8	30	3	0.8	17,650	9,650	9,509	0.539	260
								-1.8	24.4		13.1	60	12	2.5	17,070	10,250	9,823	0.575	268
								0.0	24.3		18.4	90	17	1.4	16,745	10,550	10,316	0.616	274
								0.9	23.5		10.1	120	23	1.7	16,355	10,150	9,872	0.604	280
								0.5	23.7		19.2	150	33	2.8	15,705	9,750	9,310	0.593	292
								1.4	23.2		17.1	180	43	2.8	15,055	9,450	9,028	0.600	304
								0.5	23.5		10.4	210	52	2.5	14,470	9,700	9,338	0.645	317
18	Site 1, station 200, perpendicular to shoreline	2-4	2-3	12-15	10,400	22,650	10	--	--	44, 43, 52, 59, 44 (48)	--	0	0		22,650	--	--	--	--
								0.9	6.7		18.5	30	3	0.8	22,650	12,800	12,619	0.557	194
								2.3	7.6		19.4	60	11	2.2	22,135	12,500	12,013	0.543	199
								2.7	7.2		16.1	90	15	1.1	21,875	12,800	12,559	0.574	201
								0.9	7.3		20.6	120	21	1.7	21,485	12,750	12,385	0.576	205
								1.8	7.8		16.4	150	31	2.8	20,835	11,600	11,017	0.529	211
								0.9	7.8		16.9	180	40	2.5	20,250	11,[illegible]00	10,594	0.523	217
								1.8	7.[illegible]		17.6	210	50	2.[illegible]	19,600	11,000	10,451	0.533	224
19	Site 1, station 215, 20 deg from perpendicular to shoreline (away from pier)	2-4	2-4	15-18	10,400	22,650	20	--	--	41, 55, 62, 42, 47 (49)	--		0		22,650	--	--	--	--
								0.5	18.8		16.2		3	0.8	22,650	11,400	11,219	0.495	198
								2.7	18.6		15.6		11	2.2	22,135	11,600	11,113	0.502	203
								2.3	18.5		16.4		15	1.1	21,875	12,600	12,359	0.565	205
								1.8	16.0		19.7	120	21	1.7	21,485	12,600	12,235	0.569	209
								2.7	19.0		21.5	150	28	1.9	21,030	12,200	11,800	0.561	214
								1.8	18.0		13.9	180	34	1.7	20,640	12,400	12,049	0.583	218
								2.4	17.9		15.8	210	41	1.9	20,185	12,200	11,816	0.585	222
20	Site 1, station 155, 20 deg from perpendicular to shoreline (toward pier)	2-4	2-3	15-18	10,400	22,650	30	--	--	41, 49, 62, 47, 42 (48)	--	0	0		22,650	--	--	--	--
								0.9	27.6		17.0	30	3	0.6	22,650	10,800	10,619	0.469	194
								0.9	26.1		12.3	60	11	2.2	22,135	11,300	10,813	0.489	199
								1.4	26.9		14.7	90	18	1.9	21,680	12,300	11,888	0.548	203
								2.7	27.4		17.0	120	21	0.8	21,485	12,400	12,228	0.569	205
								1.4	27.6		17.7	150	25	1.1	21,225	12,900	12,667	0.597	207
								1.8	26.6		12.8	180	28	0.8	21,030	12,800	12,632	0.601	209
21	Site 2, station 225, 20 deg from perpendicular to shoreline (toward Jet Engine Test Bldg T31)	3-5	3-4	12-15	0	12,250	10	0.1	5.2	46, 47, 72, 28, 42 (45)	15.8	0	0		12,250	6,588	--	--	--
								0.3	5.5		19.8	10	7	5.8	11,995	7,112	6,416	0.535	344
								-0.2	5.4		20.9	20	16	7.5	11,410	7,062	6,227	0.546	361
								-0.2	5.1		18.1	30	31	12.5	10,435	7,432	6,138	0.588	395
								-1.8	4.8		14.5	40	50	15.8	9,460	7,206	5,730	0.606	436
								0.0	4.5		22.9	60	56	2.5	9,460	6,754	6,518	0.689	436
								2.0	4.7		20.0	90	66	2.8	9,460	6,548	6,283	0.664	436
								1.5	4.9		24.0	120	79	3.6	9,460	6,497	6,156	0.651	436
								1.5	4.9		16.0	150	95	4.4	9,460	6,602	6,186	0.654	436

(Continued)

Table 3 (Concluded)

(1) Test No.	(2) Location	(3) Approximate Current Velocity ft/sec	(4) Wave Height ft	(5) Wave Period sec	(6) STV Payload lb	(7) STV In-Air Gross Vehicle Weight (GVW) lb	(8) Nominal STV Vehicle Speed (V) ft/min	(9) STV Pitch Angle, deg	(10) Hydraulic Horsepower Input (HTDHP) hp	(11) Cone Index (CI_{0-6})	(12) STV Slip (S), percent	(13) Approximate Distance from Shoreline ft	(14) Approximate Water Depth in.	(15) Approximate Local Slope percent	(16) STV Vehicle Effective Weight (VEW) lb	(17) Measured STV Drawbar Pull (DBP) lb	(18) DBP Corrected for Slope (DBP − VEW sin θ), lb	(19) STV Pull Coefficient ($\frac{DBP}{VEW}$ − sin θ)	(20) Sand-Track Mobility Number, N_s
22	Site 2, station 240, perpendicular to shoreline	3-5	3-4	12-15	0	12,250	30	0.2	25.0	45, 42, 60, 42, 28 (43)	19.1	0	0		12,250	6,230	—	—	—
								0.6	25.5		19.4	10	10	8.3	11,800	6,864	5,835	0.499	334
								-0.7	17.4		17.6	20	20	8.3	11,150	6,467	5,542	0.497	353
								-0.8	19.2		21.1	30	30	8.3	10,500	6,418	5,547	0.528	375
								2.1	18.0		17.2	40	40	8.3	9,460	7,100	6,315	0.668	417
								1.5	20.0		13.6	60	58	7.5	9,460	7,026	6,317	0.668	417
								1.1	20.0		16.8	90	64	1.7	9,460	6,659	6,498	0.687	417
								1.1	19.4		19.3	120	79	4.2	9,460	6,920	6,523	0.690	417
								1.3	19.3		24.8	150	110	8.6	9,460	7,152	6,335	0.670	417
23	Site 2, station 240, perpendicular to shoreline	3-5	3-4	10-12	10,400	22,650	10	1.2	6.1	43, 46, 73, 82, 35 (56)	18.4	0	0		22,650	11,160	—	—	—
								1.7	5.9		15.2	10	10	8.3	22,200	12,029	10,186	0.739	231
								1.7	5.0		16.7	20	17	5.8	21,745	11,939	10,678	0.491	236
								1.7	6.4		16.4	30	25	6.7	21,225	12,001	10,579	0.498	242
								1.5	5.8		13.7	40	32	22.5	19,470	12,034	7,751	0.398	264
								1.0	6.0		25.0	60	66	5.8	19,015	11,250	10,147	0.534	270
								0.9	6.3		14.5	90	77	3.1	19,015	11,680	11,091	0.583	270
								1.0	6.3		15.0	120	90	3.6	19,015	11,040	10,355	0.545	270
								1.4	6.1		13.9	150	101	3.1	19,015	11,593	11,004	0.579	270
24	Site 2, station 225, 20 deg from perpendicular to shoreline (toward Jet Engine Test Bldg T31)	3-5	3-4	10-12	10,400	22,650	30	-2.8	29.5	48, 48, 71, 28, 42 (47)	15.4	0	0		22,650	13,488	—	—	—
								3.0	26.6		15.5	10	10	8.3	22,200	12,676	10,833	0.488	194
								2.6	27.9		17.7	20	20	8.3	21,550	13,057	11,268	0.523	200
								1.0	28.2		21.0	30	33	10.8	20,705	13,884	11,648	0.563	208
								0.6	28.7		16.2	40	56	19.2	19,210	13,915	10,303	0.536	224
								0.6	29.2		17.9	60	63	2.9	19,015	11,750	11,199	0.589	227
								1.0	28.4		19.1	90	70	1.9	19,015	11,720	11,359	0.597	227
								1.1	29.2		19.4	120	86	4.4	19,015	11,962	11,125	0.585	227
								1.3	29.7		23.5	150	101	4.2	19,015	12,019	11,220	0.590	227

(Sheet 3 of 3)

APPENDIX A: CONSIDERATIONS RELATIVE TO POWER INPUT AND POWER EFFICIENCY

1. Hydraulic horsepower input by the onshore pumps to the STV/ hydraulic lines system was computed according to the relation

$$HYDHP = \frac{(P_1 \times F_1) + (P_2 \times F_2)}{1714} \qquad (A1)$$

where

P_1 and P_2 = pressure differential (supply minus return) at onshore pumps 1 and 2, respectively, $lb/in.^2$

F_1 and F_2 = flow rates in the return lines to pumps 1 and 2, respectively, gal/min

Values of HYDHP for the STV variable slip tests and the STV constant 20 percent slip tests are listed in column 9 of Table 2 and in column 10 of Table 3, respectively.

2. An equation that closely approximates the power efficiency of the STV mechanical and hydraulic systems defines traction power efficiency n_T as

$$n_T = \frac{TRHP}{HYDHP} = \frac{(DBP \times T)/33{,}000}{HYDHP} \qquad (A2)$$

where

TRHP = traction power, hp

DBP = vehicle drawbar pull, lb

T = vehicle track speed, ft/min

For tracked vehicle drawbar pull test conditions constant in all respects except for widely different values of slip, values of n_T remain fairly constant (i.e., n_T normalizes power efficiency data relative to slip). At large values of slip, however, n_T may have no practical meaning since vehicle speed V may be too low for the vehicle to produce useful work.

3. With a major strength and a limiting weakness of n_T noted, the following tabulation lists average values of n_T, separated by nominal values of track speed T, for the 24 STV tests reported herein:

T = 12.5 ft/min		T = 25.0 ft/min		T = 37.5 ft/min	
Test No.	η_T	Test No.	η_T	Test No.	η_T
1	0.68	2	0.45	3	0.33
4	0.71	13	0.50	5	0.32
6	0.71	16	0.53	7	0.34
8	0.80	19	0.57	9	0.40
10	0.82	Avg	0.51	11	0.39
12	0.70			14	0.52
15	0.65			17	0.46
18	0.71			20	0.51
21	0.59			22	0.35
23	0.76			24	0.47
Avg	0.71			Avg	0.41

4. Figure A1 illustrates the average relation of η_T to T based on the above data. The fact that STV track speed T appears to

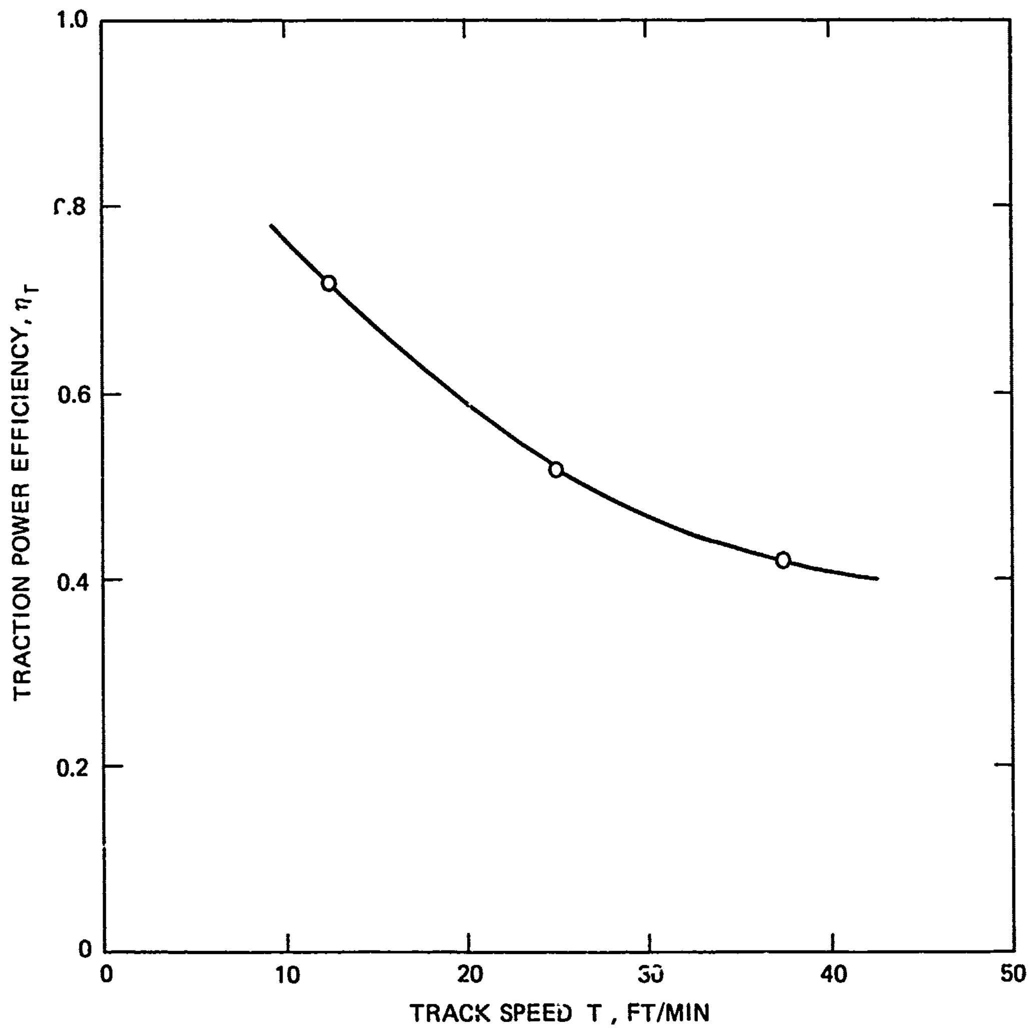


Figure A1. Average relation of η_T to T based on the STV test results

have a major influence on η_T arises primarily because T is almost directly proportional to the hydraulic system flow rate; thus, the η_T versus T relation largely reflects STV hydraulic system behavior.

5. The relation in Figure A1 is applicable only for the particular STV/hydraulic lines/power source combination whose test results are reported herein. For this combination, STV η_T performance decreases (but at what appears to be a diminishing rate) as track speed T increases. In a qualitative sense, this type of relation almost certainly holds for any tracked vehicle powered hydraulically through lines covering a sizeable distance to a remote power source; i.e., η_T can be expected to decrease as track speed increases. However, the particular quantitative relation of η_T to T for a given tracked vehicle/hydraulic lines/power source/beach and nearshore environment situation depends on many factors: mechanical and geometric characteristics of the tracked vehicle, length and diameter of the hydraulic lines (flow losses), operational characteristics of the power source, viscosity characteristics and operating temperature of the particular hydraulic fluid used, water temperature, tracked vehicle-soil interactions (to a limited degree), etc. At this point, the relations of η_T to T for particular remotely powered tracked vehicles must be determined on a case-by-case basis.

6. Finally, to supplement the η_T versus T relation described to this point, consider the relation of drawbar power efficiency η_{DB} to the tracked vehicle speed V (in ft/min). The definition of η_{DB} is:

$$\eta_{DB} = \frac{DBHP}{HYDHP} = \frac{(DBP \times V)/33{,}000}{HYDHP} \tag{A3}$$

where

DBHP = drawbar power, hp

Because $V = T(1 - \text{slip})$, $\eta_{DB} = \eta_T(1 - \text{slip})$. Thus, for a constant value of slip, η_{DB} is related to V in the same way that η_T is related to T , save for the constant (1 - slip). For example, at 20 percent slip (an important nominal slip value since it represents a

good balance in terms of high vehicle drawbar pull and tractive efficiency performance (see paragraphs 33-41 in the main text)), the relation of η_{DB} to V is the same as the relation of $\eta_T(1 - 0.2)$ to $T(1 - 0.2)$. For the 24 STV tests, then, the relation of η_{DB} to V at 20 percent slip can be defined by multiplying each η_T value and each T value in the paragraph 3 tabulation by 0.8.

7. For tracked vehicle drawbar pull test conditions constant in all respects except for widely different values of slip, η_{DB} has the disadvantage of not normalizing values of power efficiency relative to slip, so that values of η_{DB} vary widely. At a particular constant slip level, however, η_{DB} has the slight advantage of directly measuring useful power efficiency (since DBHP in the numerator of η_{DB} expresses <u>useful</u> drawbar power (drawbar pull DBP delivered at over-the-ground vehicle speed V)), while η_T must be multiplied by (1 - slip) to express this same relation.

APPENDIX B: NOTATION

1. A listing of the definitions and units of all symbols used in the computer subroutines of STAM was supplied to CEL as part of the work related to the previous study. No changes in that listing occurred as a result of the study described in this report.

2. The following listing includes all notations used in this report.

ACG	Angle formed at the vehicle pivot point by one line parallel to the bottom of the vehicle's track and a second line that passes through the vehicle's center of gravity
ATS	Area of one track shoe
b	Distance between center lines of vehicle tracks
BN	Number of track bogies in contact with a single vehicle track over nominal track-ground contact length TL
CG	Center of gravity
CGF	Horizontal distance from vehicle CG to center line of front road bogie
CGH	Vertical distance from vehicle CG to center line of road bogies
CI	Cone index
CI_{0-6}	Average cone index within the 0- to 6-in. soil layer
d	Distance from the center of the vehicle rear road wheel to a vertical line through the vehicle's CG (with the vehicle resting on a flat, level, unyielding surface)
DBHP	Drawbar power
DBP, DBP_{20}	Vehicle drawbar pull and vehicle drawbar pull at 20 percent slip, respectively
DCG	Distance from vehicle CG to pivot point on back end of vehicle track
DRISCG	Direct distance from vehicle CG to center of rear idler or sprocket
DRYWT	Dry weight of the vehicle (equals in-air gross vehicle weight (GVW))
DS	Distance vehicle spans over a ditch before significant vertical motion of the vehicle begins
DSS	Drive sprocket speed

EFF	Transmission efficiency (use 0.95 if not given)
F	Flow rate
FDR	Final drive ratio
FDREF	Final drive efficiency
FLEW	Maximum force that leading edge of vehicle can withstand
G	Cone index gradient
GC	Vehicle ground clearance
GH	Grouser height
GVW	Gross vehicle weight
GVW_t	Gross vehicle weight that causes maximum deflection of the road bogies (i.e., causes the road bogies to "bottom out")
HAA	Height of rigid point at front of tracked vehicle used in the determination of the vehicle approach angle VAA
HLE	Height of leading edge of vehicle
hp	Horsepower
HPT	Horsepower per ton GVW (or per ton VEW if vehicle buoyancy is taken into account)
HRIS	Vertical distance from ground to center of rear idler or sprocket
HYDHP	Hydraulic horsepower input
j	Vertical distance from vehicle CG to the ground when the vehicle rests on a flat, level, unyielding surface
J_o	Moment of inertia of the vehicle mass about a point O at the center of the bottom of one of the vehicle's tracks, when the vehicle is viewed from the end
J_p	Moment of inertia of the vehicle mass about a point P at the bottom, rearmost point of the vehicle's tracks, when the vehicle is viewed from the side
ℓ_1, ℓ_2	For TLC divided into two parts by the intersection of the vertical projection of the vehicle's CG , ℓ_1 and ℓ_2 are the shorter and longer parts of TLC , respectively
M	Torque input to the vehicle drive sprockets
n	Exponent in the term $\left(\frac{d}{TLC/2}\right)^n$, which is part of N_s
N_s	Sand-track mobility number
N'_s	Sand-track mobility number modified to account for vehicle submergence

P	Pressure differential
PC_{20}	Pull coefficient at 20 percent slip (equals DBP_{20}/VEW , $(DBP_{20}/VEW) - \sin\theta$, or $(DBP_{20}/VEW) + \sin\theta$ for a vehicle operating on level ground, on a downslope of θ deg , or on an upslope of θ deg , respectively)
r	Drive sprocket pitch radius
REC	Height of vehicle's trailing edge
RISR	Distance from center of rear idler or sprocket to outermost edge of track
RWR	Road wheel radius (plus track thickness)
RWW	Drive sprocket pitch radius
S	Slip (of the vehicle's running gear relative to the ground)
SP	A classification of sandy soils according to the Unified Soil Classification System
STAM	Surfzone Transition Analytical Methodology
STV	Surfzone Test Vehicle
SUBWT	Submerged weight of vehicle
T	Track speed
TE	Vehicle tractive efficiency
TF	Tractive force
TF_0	Tractive force required for obstacle override
TF_1	Tractive force required to overcome soil motion resistance and slope resistance (due to vehicle weight)
TF_2	Sum of TF_0 and TF_1
TL	Track length between centroids of outermost road bogies
TLC	Track length in contact with ground
TMR	Total motion resistance
TN	Number of tracks
TRHP	Traction power
TT	Track type
TVAR	Transmission type (0 = automatic, 1 = manual)
TW	Track width
V	Vehicle speed
VAA	Vehicle approach angle
VDA	Vehicle departure angle

VEW	Vehicle effective weight (equals gross vehicle weight with buoyancy taken into account)
VEW_t	Vehicle effective weight that causes maximum deflection of the road bogies (i.e., causes the road bogies to "bottom out")
VHF	Vehicle height in feet
VL	Vehicle length (overall)
VT	Vehicle type
VW	Vehicle width (overall)
VWF	Vehicle width in feet
XBC	Vehicle braking coefficient
η_{DB}	Drawbar power efficiency
η_T	Traction power efficienty
ω	Angular velocity of the vehicle drive sprockets
θ	Seafloor slope

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Turnage, Gerald W
  Partial field validation of the Surfzone Transition Analytical Methodology (STAM) / by Gerald W. Turnage. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1980.
  59, [16] p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; GL-80-6)
  Prepared for Civil Engineering Laboratory, U. S. Naval Construction Battalion Center, Port Hueneme, Calif.

1. Coastal zone. 2. Mathematical models. 3. Mobility. 4. Ocean bottom vehicles. 5. Surfzone Transition Analytical Methodology (STAM). 6. Trafficability. 7. Vehicle performance. I. United States. Naval Construction Battalion Center, Port Hueneme, Calif. Civil Engineering Laboratory. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; GL-80-6.